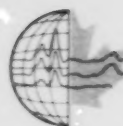




Ministry of
Northern Development
and Mines

Mines and
Minerals
Division



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Exploration **87**
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Proceedings of Exploration '87

**Third Decennial International Conference on
Geophysical and Geochemical Exploration for
Minerals and Groundwater**

**Ontario Geological Survey
Special Volume 3**

**Edited by
G.D. Garland**

Compliments of
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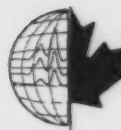
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ERRATA FOR EXPLORATION '87

The following errors occurred during the publishing process. These errors have been corrected, and are printed in this folio. This folio should be placed within your volume for easy reference.

1. The incorrect sun angles were placed alongside Photos 11.3a and 11.3b. These plates have been reproduced on the accompanying folio so that the sun angles are positioned alongside the correct photo.
2. Photos 41.1 and 41.2 did not reproduce well on the printed page. These plates have been printed correctly in the folio.
3. Plates 31.1 and 31.2 were not printed at all in the colour folio. These are reproduced in this errata.

The publications committee for Exploration '87 and the Ontario Geological Survey regret any inconvenience these errors have caused the authors especially, and the readers in particular.

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Photo 11.3a. Northeast Ontario; monochrome representation of aeromagnetic data with a northeast sun illumination angle.

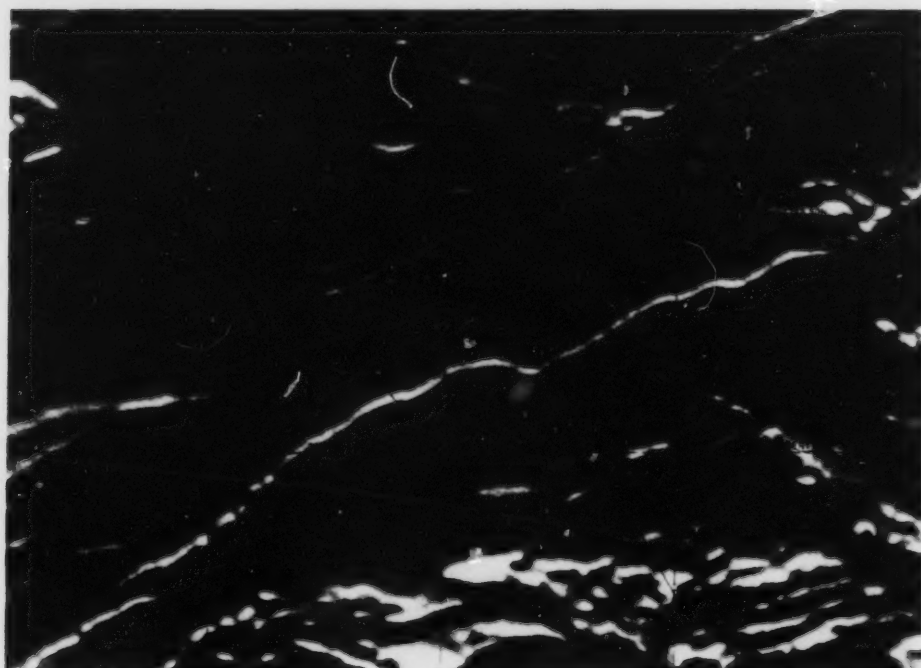


Photo 11.3b. Same data with a north sun illumination angle (courtesy of Dighem Surveys and Processing, Incorporated).

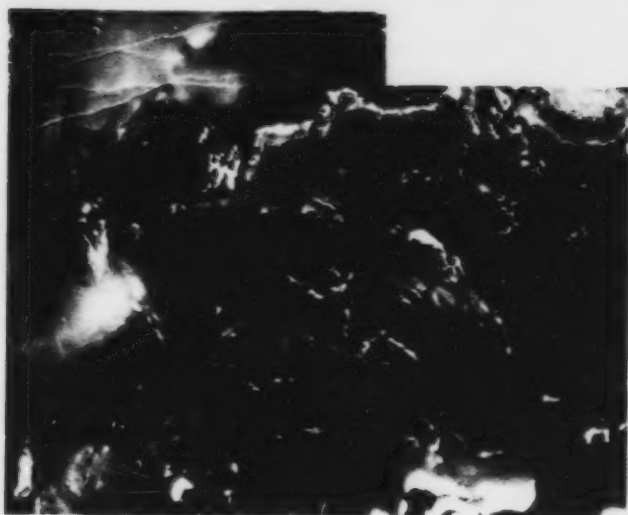


Photo 41.1. Image of the aeromagnetic data covering the Witwatersrand Basin (lighter shades represent positive anomalies; darker shades, negative anomalies).

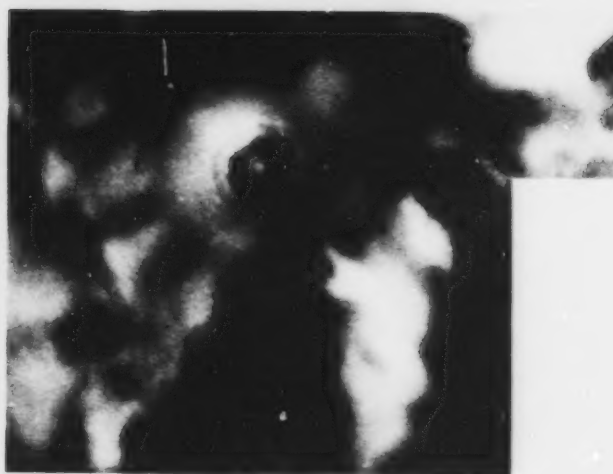


Photo 41.2. Image of the Bouguer gravity data covering the Witwatersrand Basin.



Plate 31.1. Combined image of negative gravity anomalies and high uranium content in stream sediments which identify HHP uraniferous granites in Scotland.

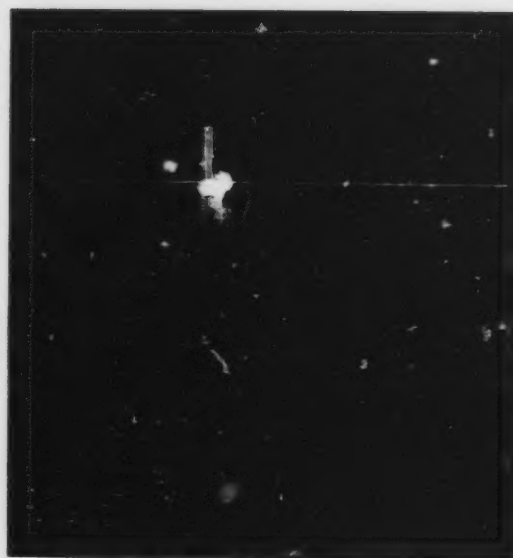


Plate 31.2. Combined image of Pb, Cu and Ag over the English Lake District and northern Pennines. Note the change in colour of anomalies between the plutonic and volcanic associated mineralisation (mainly red-orange) of the Lake District (west) and the modified MVT type mineralisation (mainly blue-green) of the northern Pennines (east).



Preface and Acknowledgments

INTRODUCTION

Exploration '87, the Third Decennial International Conference on Geophysical and Geochemical Exploration for Minerals and Groundwater, was held in Toronto, Canada from September 27 to October 1, 1987. It constitutes a successor to two prior conferences, namely the Canadian Centennial Conference on Mining and Groundwater Geophysics, held in Niagara Falls, Canada in 1967, and Exploration '77, an International Symposium on Geophysics and Geochemistry Applied to the Search for Metallic Ores, held in Ottawa, Canada in 1977.

This meeting provided a forum for both formal and informal exchanges of ideas and opinions in the realm of exploration technology, among 945 delegates from 76 countries. A total of 77 invited papers was presented orally and 76 additional papers were presented in poster form.

Prior to the conference proper, two field schools were held, one on geophysical methods and the other on geochemical methods. These were attended by a total of 50 delegates from 26 countries.

A technical exhibition was assembled wherein 66 exhibitors from nine countries displayed their latest exploration equipment and services.

This Proceedings Volume presents the full text of the invited papers from Exploration '87, with the exception of several papers which are available in abstract form only. Papers (and abstracts) have been published only in the language of their presentation, that is, in English or French. Due to limitations of space and budget, it was, unfortunately, not feasible to present second language translations of either the abstracts or the text of these papers.

For the same reasons, it was not feasible to include the text of any of the many excellent poster papers that were presented at Exploration '87. The Organizing Committee is currently encouraging the publication of these worthy poster papers in alternative publications.

Exploration '87 was planned and organized by a committee of the Canadian Geoscience Council (the Organizing Committee), with the support of the Society of Exploration Geochemists, the Canadian Exploration Geophysicists, the Canadian International Development Agency (CIDA), the Ontario Ministry of Northern Development and Mines, and the Women's Association of the Mining Industry of Canada (W.A.M.I.C.). To CIDA, we are indebted for support for 50 delegates, half of whom attended the preceding field schools, from 25 countries, as well as a contribution directed towards the present Proceedings Volume.

The Ontario Ministry of Northern Development and Mines have graciously provided a grant toward publication of the Conference Proceedings Volume. The Ministry has also provided support and preparation of the volume for printing through the Scientific Review Office of the Ontario Geological Survey, part of the Mines and Minerals Division.

The Honorary Chairman of Exploration '87 was the honourable Gerald S. Merrithew, Minister of State, Forestry and Mines, Canada.

The abundant success, in every respect, of Exploration '87, is a tribute to the many individuals, largely drawn from within the Canadian geoscience community, who voluntarily and unselfishly donated their talents and valuable time during the three years of planning and execution of this conference, and of its preceding field schools. Thanks are also due the authors for their hard work and diligence, both in preparing their papers initially for presentation and later in the marshalling of their texts for publication.

The following were members of the Organizing Committee for Exploration '87:

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General Chairman

EDITOR'S INTRODUCTION

These Proceedings of Exploration '87 follow the precedents so well established by Exploration '67 and Exploration '77. The past two years have seen great advances in methods of displaying geophysical and geochemical results through the use of computer graphics with colour. In this volume we have included a section of colour images, although this has required that some illustrations are physically separated from the papers of which they form a part.

As in the case of past volumes, each paper was critically read by one or more reviewers. It is a pleasure to acknowledge the time and care devoted by our critical readers, whose efforts have ensured a high standard. They are:

R.C. Bailey	F. Jagodits
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P.G. Hallof	W.E.S. Urquhart
H. Halls	R.H. Wallis
P.J. Hood	G.F. West

In order that the Proceedings form a permanent record of the conference, we have included the abstracts of those presented papers for which no manuscript was available.

The volume was prepared for the printer with the assistance of the Scientific Review Office of the Ontario Geological Survey. The organizers of Exploration '87 are greatly indebted to V.G. Milne, Director of the Ontario Geological Survey, for his encouragement and support, to Trudy Scott, Manager of the Scientific Review Office, and to Guy Kendrick, Review Geologist, who carried out the preparation. The contribution of the following Ontario Geological Survey personnel toward the preparation of the volume is gratefully acknowledged; Raimonds Balgalvis, Sharon Daniel, Esmeralda Garcia, David Gilmore, Carol Hazen, Virginia Kanary, Jason Reid, Michelle Sauve, Ronald Steenstra, Monika Sutton, Christine Tchoryk, James Boyd, and Alison Weatherston.

Throughout the process of assembling the papers and arranging for their review, the Publications Committee has been greatly assisted by its secretary, Mrs. Lillian Vincze, to whom special acknowledgment is due.

George D. Garland, *Chairman*

Arthur Darnley

Norman R. Paterson

Publications Committee

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SI Unit	Multiplied by	Gives	Imperial Unit	Multiplied by	Gives
LENGTH					
1 mm	0.039 37	inches	1 inch	25.4	mm
1 cm	0.393 70	inches	1 inch	2.54	cm
1 m	3.280 84	feet	1 foot	0.304 8	m
1 m	0.049 709 7	chains	1 chain	20.116 8	m
1 km	0.621 371	miles (statute)	1 mile (statute)	1.609 344	km
AREA					
1 cm ²	0.155 0	square inches	1 square inch	6.451 6	cm ²
1 m ²	10.763 9	square feet	1 square foot	0.092 903 04	m ²
1 km ²	0.386 10	square miles	1 square mile	2.589 988	km ²
1 ha	2.471 054	acres	1 acre	0.404 685 6	ha
VOLUME					
1 cm ³	0.061 02	cubic inches	1 cubic inch	16.387 064	cm ³
1 m ³	35.314 7	cubic feet	1 cubic foot	0.028 316 85	m ³
1 m ³	1.308 0	cubic yards	1 cubic yard	0.764 555	m ³
CAPACITY					
1 L	1.759 755	pints	1 pint	0.568 261	L
1 L	0.879 877	quarts	1 quart	1.136 522	L
1 L	0.219 969	gallons	1 gallon	4.546 090	L
MASS					
1 g	0.035 273 96	ounces (avdp)	1 ounce (avdp)	28.349 523	g
1 g	0.032 150 75	ounces (troy)	1 ounce (troy)	31.103 476 8	g
1 kg	2.204 62	pounds (avdp)	1 pound (avdp)	0.453 592 37	kg
1 kg	0.001 102 3	tons (short)	1 ton (short)	907.184 74	kg
1 t	1.102 311	tons (short)	1 ton (short)	0.907 184 74	t
1 kg	0.000 984 21	tons (long)	1 ton (long)	1016.046 908 8	kg
1 t	0.984 206 5	tons (long)	1 ton (long)	1.016 046 908 8	t
CONCENTRATION					
1 g/t	0.029 166 6	ounce (troy)/ ton (short)	1 ounce (troy)/ ton (short)	34.285 714 2	g/t
1 g/t	0.583 333 33	pennyweights/ ton (short)	1 pennyweight/ ton (short)	1.714 285 7	g/t

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1 ounce (troy) per ton (short)	20.0	pennyweights per ton (short)
1 pennyweight per ton (short)	0.05	ounces (troy) per ton (short)

Note: Conversion factors which are in bold type are exact. The conversion factors have been taken from or have been derived from factors given in the Metric Practice Guide for the Canadian Mining and Metallurgical Industries, published by the Mining Association of Canada in cooperation with the Coal Association of Canada.



The Role of Exploration in Resource Development



1. Mineral Exploration Economics: Focusing to Encourage Success

Brian W. Mackenzie

Department of Geological Sciences and Centre for Resource Studies, Queen's University, Kingston, Ontario, Canada K7L 3N6.

ABSTRACT

At the start of exploration, all finding, development, and production activities represent controllable choices. Thus, there is the widest possible scope for focusing investment to encourage success. Successful exploration results in the discovery and delineation of economic mineral deposits. Economic guidelines are required from the outset to screen out the many unprofitable programs and projects, so that investment can be channeled along those few paths which are perceived to be particularly attractive. The ability to judiciously control the cost, risk, and return characteristics of the search process in this way provides a unique opportunity to enhance exploration efficiency.

The purpose of the paper is to describe this strategic area of opportunity, drawing on empirical studies of exploration economics carried out in Canada and Australia over a 15-year period. First, the exploration procedures and economic evaluation concepts which underly this work are outlined. Then, illustrations are presented to show key exploration characteristics which provide control opportunities, including: the cost of exploration success, discovery risk, the variability of returns among economic deposits, the impact of the multi-billion dollar discovery, time trends, and the issue of geographical selectivity. Several mining company case studies are presented to demonstrate the opportunity generally available to focus exploration in a way which encourages success. Finally, attention is turned to the ingredients of exploration success.

INTRODUCTION

The mineral supply process proceeds from exploration through development to production. Investment starts with the search for economic mineral deposits. Thus, mineral exploration occupies a strategic up-front position in the supply process. At the beginning, all finding, development, and production activities represent controllable choices. It is the only time a mining company is not committed to particular programs, projects, or mines. In other words, at the start of exploration there are no sunk costs. Thus, there is the widest possible scope for focusing investment to encourage success. If these strategic choices are made judiciously, exploration will be

characterized by a rich cost-risk-reward relationship.

The way in which mineral exploration works is determined by its high risk nature. Thus, exploration comprises a large number of sequential information-gathering steps. Decisions are made at the end of each step as to whether or not to continue. Under conditions of high risk, it is important to limit the cost of the search process in this way by selecting and concentrating on only those few situations which are perceived to have economic potential. Thus, a phased approach to exploration is essential.

The economics of mineral exploration is measured by the relationship between real exploration expenditures and the value of economic deposits discovered as a result of that exploration. Changes in exploration economics over time reflect the effects of depletion, and advances in geologic concepts and exploration technology. The procedure for assessing the economics of mineral exploration involves a number of considerations associated with expected value criteria and risk measurement.

From an economic viewpoint, key characteristics of mineral exploration include:

1. the direct cost of success
2. the time cost of exploration
3. discovery risk and its practical implication
4. variability of returns among economic discoveries
5. effect of the multi-billion dollar discovery
6. exploration dynamics
7. geographical variability

These characteristics give rise to opportunities for mining companies to focus their activities to encourage success.

The purpose of the paper is to provide illustrations of the key exploration characteristics and of the results of exercising control on mineral exploration economics. The examples used draw on empirical work carried out in Canada and Australia from 1970. Finally, these experiences lead us to consider the ingredients of exploration success.

THE WAY IN WHICH EXPLORATION WORKS

There is an economic reason for breaking exploration into a number of sequential steps. Since explo-

ration is a high risk activity, this type of phased structure is required to minimize the cost of carrying the many uneconomic situations through the sequential steps by rejecting them as soon as they are perceived to be unattractive. At the same time, care must be taken to prevent the rejection of potentially economic deposits by being too selective at too early a stage. Thus, selectivity attempts to balance the costs associated with these two types of error. In order to do this, each exploration opportunity at each step must be subjected to and satisfy technical and economic viability tests to justify advancement to the succeeding step.

The sequential exploration progression advocated may be illustrated by examining a particular exploration program. While each exploration program has its own special features, the stages, costs, and selectivities associated with this illustrative case may, for our purposes, be considered generally representative of how metallic mineral exploration works.

The illustrative exploration program, directed to the discovery of massive sulphide deposits in the shield region of Canada, is described in Appendix A and summarized in Figure 1.1. In this case, there are five main exploration stages. The third stage, exploratory drilling, comprises three sub-stages. The purpose of the first two stages is to define discrete exploration opportunities. Then, the subsequent stages test and screen these opportunities, endeavouring to reject those which are unattractive as soon as possible and concentrate on those which show economic potential.

As specified in Appendix A, costs are associated with each exploration activity. These expenditures may be aggregated in various ways for purposes of economic evaluation. Since the starting point of the illustrative exploration program is the selection of favourable 500 km² areas, it is convenient here to express the program expenditures on this basis. As shown in Table 1.1, the cost of exploring a 500 km² area from start to finish averages out to \$584 000. The exploratory drilling stage accounts for almost half of this and, together with the ground follow-up stage, represents more than three-quarters of the overall program expenditure. Area selection is not a large cost item here because the development of appropriate geological models and exploration concepts within the environment of interest are utilized to select many areas. At the other end of the program, delineation drilling expenditures are shown to be modest, mainly because of the small chance (about 1 in 20 in this case) that exploration of an area will discover an occurrence sufficiently attractive to justify delineation. More generally, Table 1.1 illustrates the correct way to compare exploration expenditures from an economic viewpoint, averaged out to a common standard, a 500 km² area in this case.

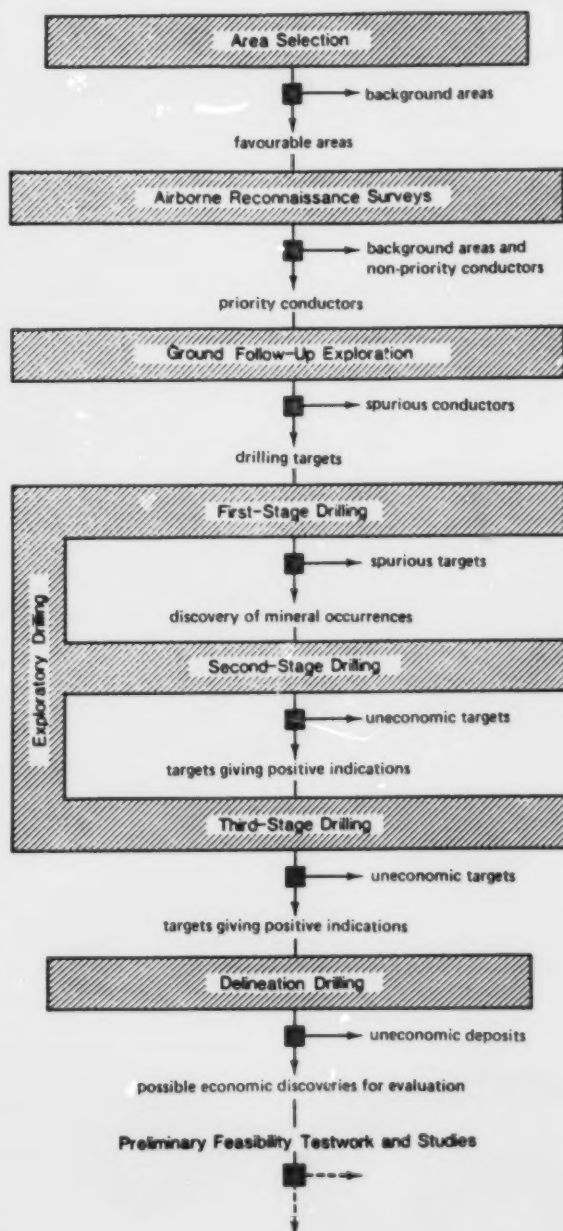


Figure 1.1. Illustrative sequential exploration program.

As indicated in Figure 1.1, decisions are taken at the end of each stage and sub-stage as to whether or not to continue exploration in the light of the information accumulated and analyzed. The exploration organization exercises control over the search process by selecting at each decision point only those few opportunities which are perceived to have economic potential. This is why the average cost of exploring a favourable 500 km² area is only \$584 000.

TABLE 1.1. AVERAGE COST OF ILLUSTRATIVE EXPLORATION PROGRAM (BASED ON 500 KM² AREA).

Stage	Exploration Expenditure	
	(\$)	(%)
Area Selection	20 000	4
Airborne Reconnaissance	72 000	12
Ground Follow-Up	171 000	29
Exploratory Drilling		
First-Stage	207 000	36
Second-Stage	54 000	9
Third-Stage	19 000	3
Total	280 000	48
Delineation Drilling	41 000	7
Total Program	584 000	100

Alternatively, let us hypothetically evaluate what the cost would be if the exploration organization applied no control beyond the ground follow-up stage, fully exploring each of the 30 priority conductors defined. Under these circumstances, the unit costs specified in Appendix A are reworked to show that the average exploration cost for an area would be \$27 338 000 as compared to \$584 000! While this type of saturation exploration approach might conceivably be of scientific interest, and would indeed insure that any economic deposit underlying the 30 conductors would be discovered, it is obviously absurd in economic terms. The comparison highlights the need for a phased approach to exploration, with decisions taken at the end of each stage on the basis of technical and economic criteria.

The control exercised within the simplified exploration program is summarized in Table 1.2. Selectivity is measured here by the number of times that the scope of exploration activity is reduced and the focus of exploration concentrated in each stage.

For example, the area selection stage, starting with the broad exploration environment of interest (which may vary in size from several tens of thousands of square kilometres to several hundreds of thousands of square kilometres), results in the definition of a favourable 500 km² area. Thus, the selectivity exercised at this stage is at least 50 times.

As exploration proceeds within the area, the focus becomes increasingly focused — from 500 km², to 30 priority conductors (covering 30 km²), to 18 drilling targets, to a 0.9 chance of discovering a mineral occurrence, and so on. Eventually, as shown in Table 1.2, there is only a 0.054 probability that the program will discover a deposit sufficiently attractive to justify delineation drilling, and, as a result, a 0.027 chance of a possible economic discovery warranting preliminary feasibility testwork and studies.

The purpose of this illustration is to show the way in which exploration works. Because exploration is such a high risk activity, programs should be very broadly based, starting with an environment of interest and the selection of large priority areas within the environment. Then, exploration should be increasingly focused by selecting and concentrating on only those few situations which are perceived to have economic potential. By limiting the cost of failure, a phased approach to exploration conserves scarce human and financial resources so that they can be concentrated on the more promising opportunities. Also, within fixed budget constraints, the exploration organization is able to improve its chances of success by selecting more areas and initiating more exploration projects than would otherwise be possible.

ECONOMICS OF MINERAL EXPLORATION

Mineral exploration cannot be justified as an end in itself. The economics of mineral exploration is determined by the costs, risks, and returns associated with the three-phase mineral supply process. What economic concepts and criteria should be applied so

TABLE 1.2. CONTROL EXERCISED WITHIN ILLUSTRATIVE EXPLORATION PROGRAM (BASED ON 500 KM² AREA).

	Exploration Scope		Selectivity*
	Before Decision	After Decision	
Area Selection	environment	500 km ²	50+
Airborne Reconnaissance	500 km ²	30 conductors	16.7
Ground Follow-Up	30 conductors	18 targets	1.7
Exploratory Drilling			
First-Stage	18 targets	0.9 targets	20
Second-Stage	0.9 targets	0.18 targets	5
Third-Stage	0.18 targets	0.054 targets	3.3
Delineation Drilling	0.054 targets	0.027 targets	2

* Ratio of exploration scope prior to making a decision to exploration scope afterwards. In other words, selectivity measures the number of times that the scope is reduced and the focus of exploration concentrated as a result of the control exercised by the exploration organization.

that exploration activities can be focused to encourage success?

ECONOMIC PARAMETERS

Two definitions are required to crystallize the cost, risk, and return characteristics of mineral exploration.

1. The "discovery of a mineral occurrence", the result of successful primary exploration, represents a technical or geological success. Although somewhat arbitrary, it is most conveniently defined with respect to a particular decision point in the sequential exploration process. For example, in the illustrative exploration program (Appendix A), the discovery of a mineral occurrence is considered to occur when indications of potentially economic grades across mineable widths are obtained, usually by drilling. As shown in Figure 1.1, such indications are associated with an exploration target being taken from first to second stage exploratory drilling. The distribution of mineral occurrences in nature is such that it is highly improbable such a discovery will subsequently prove to be of sufficient quality to be economically viable.
2. An "economic mineral deposit", the focal point of the mineral supply process, usually has to satisfy both minimum acceptable size and profitability criteria when evaluated for a specified set of economic and technological conditions. These hurdles are specific to the exploration organization concerned and can have an important effect on exploration economics.

The economics of mineral exploration, and therefore exploration decisions, should reflect the perceived costs, risks and returns of exploration. These parameters may now be conceived of in terms of C, p, and R, where:

- C = typical or average exploration cost associated with the discovery of a mineral occurrence
p = probability of an economic mineral deposit given the discovery of a mineral occurrence
R = average return associated with an economic mineral deposit

Thus, C represents the exploration expenditure required for a technical success. R is the motivator of the search process, the return or prize resulting from an economic discovery. The connecting link between the exploration cost and return is the discovery risk: the chance or probability of success each time, p.

In general, mineral exploration is characterized by a high discovery risk, and a large possible return from an economic discovery relative to the cost of discovering a mineral occurrence. In this sense, mineral exploration is analogous to games of chance.

However, the ability to control C, p, and R provides mining companies with a great opportunity.

It is sometimes convenient to combine the cost and risk parameters in a single measure. Thus:

$$E = C/P$$

where,

E = average exploration cost required to find and delineate an economic mineral deposit

E may be directly evaluated by dividing total exploration expenditures by the estimated number of economic discoveries. While this measure veils the concept of discovery risk, a key characteristic of mineral exploration, it can be conveniently applied, as we will see, to evaluate the implications of that discovery risk for the mining company.

INVESTMENT CRITERIA

These cost, risk, and return parameters are applied to measure the economic attractiveness of investment in mineral exploration. Exploration investment criteria are subdivided into long-term and short-term considerations. The long-term attractiveness of exploration is evaluated using various measures of expected value. The short-term problems associated with realizing expectations are assessed by risk criteria.

Expected Value

Expected value measures the average value that exploration yields in the long-term, when the successes and failures associated with a very large (theoretically infinite) number of discoveries are considered. The expected value of exploration is derived from the time distribution of average cash flows for the discovery of an economic mineral deposit, as portrayed in Figure 1.2. Because of time value considerations, the average cash flow characteristics must be brought to a common point in time or spread evenly over a common period of time to make a valid assessment.

The following two measures of expected value are applied in this paper.

1. Expected Value per Economic Discovery

An exploration expenditure, E, is required on average for the discovery and delineation of an economic deposit, yielding an average return, R. Thus:

$$EV = R - E$$

where,

$$E = C/P$$

2. Expected Rate of Return

The expected discounted cash flow rate of return on investment may also be evaluated based on the time distribution of average cash flows for an economic deposit as depicted in Figure 1.2. By definition, rate of return is the discount rate

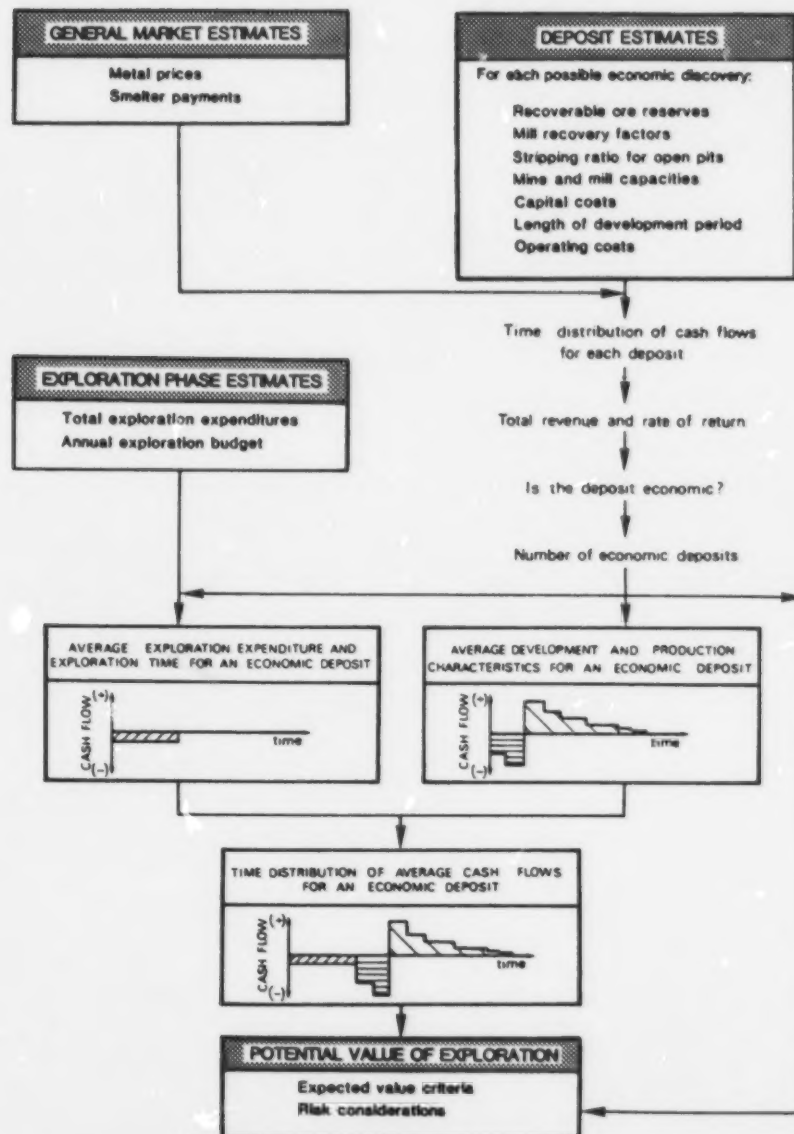


Figure 1.2. Time distribution of average cash flows for an economic deposit.

that equates the present value of the positive cash flows with the present value of the investment. In economic terms, rate of return is the average percentage annual return that exploration is expected to yield over the life of the mineral supply cycle. Using this method, the minimum acceptable condition for investment is an expected rate of return equal to the cost of capital.

Expected values are broadly assessed on the basis of overall exploration activity and reflect the average performance of all organizations that have undertaken exploration in a country or region. Obvi-

ously there are benefits to be gained from the application of superior skills and selectivity. In exploration environments characterized by unacceptable overall expected values, the selection of opportunities of above-average merit is a necessary condition for long-term exploration success. This can only result from the application of superior exploration skills, developed within a mining company over time through continued exposure to particular environments of interest.

Risk Considerations

Three types of risk are associated with the realization of exploration expectations. Individually and

collectively, these risks present challenges to the long-term profit, survival, and growth of organizations active in mineral exploration. They are:

1. the risk caused by the sensitivity of mineral exploration economics to metal price uncertainties
2. the risk related to the uncertainty of the return, given an economic discovery, due to geologic variability among economic deposits
3. the risk associated with the discovery of economic mineral deposits

The first type of risk is associated with the materials market for mineral commodities. There is typically a high level of uncertainty associated with the forecasting of short-term fluctuations and long-term trends in mineral market prices, including exchange rate risks. The economics of mineral exploration is highly sensitive to anticipated prices. Flexibility is required in the exploration planning process to contend with unexpected changes in market conditions, which are inevitable. Among the exploration strategies that can be adopted to address this risk is that of directing exploration toward polymetallic deposits.

The second type of risk is the variability of the return due to geologic factors, given the discovery of an economic mineral deposit. The downside risk and upside potential associated with the variability of geologic parameters among deposits have, as we will see, important implications for exploration planning.

The third and most direct risk faced in mineral exploration is the discovery risk: the low probability — typically a 1 to 2 percent chance of finding an economic mineral deposit, given the discovery of a mineral occurrence. The implications of discovery risk for the exploration organization should be assessed. Because this risk is so high, the application of limited organizational funds does not ensure the realization of expected values, and exploration resources are often expended without success.

The practical implication of discovery risk for an exploration organization is that there is a large difference between the average exploration cost required to find and delineate an economic deposit and the exploration funds required to ensure success. The relevant relationships are as follows.

$$P_1 = 1 - e^{-m}$$

where,

$$A = -E [\ln(1 - P_1)]$$

Thus,

$$m = A/E$$

where,

P_1 = probability of discovering at least one economic deposit

A = exploration funds available over appropriate planning horizon

E = average exploration cost required to find and delineate an economic deposit

e = 2.71828

$\ln$ = natural logarithm

For example, the exploration funds required to be 90 percent sure of discovering at least one economic deposit are 2.3 times the average exploration cost associated with an economic discovery¹.

EMPIRICAL EVALUATION PROCEDURE

The methodology described here is based on the author's confidence in the value of providing, insofar as is practically possible, a factual economic basis for mineral exploration; of assessing exploration performance in terms of conventional measures of economic value; and of studying the past as a practical guide to planning for the future.

In this paper, the economics of mineral exploration is assessed on a before-tax potential-value basis². All direct costs and revenues through the exploration, development, and production phases of mineral supply are included.

The potential value of mineral exploration is defined as the difference between the revenues realized from mineral production and all the costs required to realize that revenue, including an allowance for the cost of capital. Since the cost of capital is deducted, this potential value represents the increase in real wealth that results from investing in exploration rather than in some other economic activity³. Thus, the potential value reflects both the quality of mineral endowment and the economic viability of exploration. It also measures the productive capability of mineral resources and represents what is available for sharing between industry and government before mining taxation considerations.

The expected value and risk characteristics of mineral exploration are evaluated on the basis of historical footprints. Two assumptions are necessary if the results are used in planning for the future. First, deposits yet to be found must resemble, in economic terms, those that have been found to date. Second, the cost of making a future discovery must be similar to the cost in the past.

$$^1 A = -E[\ln(1 - .90)] = -E[-2.3] = 2.3 E.$$

² The examples presented in this paper do not deal with mining taxation and royalties and how they affect the economics of mineral exploration from the viewpoint of the mining company. While this would more fully address the question of investment incentive to a mining company deciding on new or continuing exploration programs, the procedure used measures the economic value of exploration from the viewpoint of society as a whole.

³ The cost of capital is a real cost which affects the new wealth created by mineral exploration.

Thus, assessment of the cash flow characteristics associated with mineral exploration is based on actual experience over a relevant historical time period. This information is then placed in the context of current outlook conditions.

In essence, the methodology (see Figure 1.3) follows these steps.

1. Total exploration expenditures are estimated for the historical time period of interest.
2. Significant deposits discovered as a result of these expenditures are classified by discovery date and listed for evaluation.
3. The cash flow characteristics of the development and production phases for each of these possible economic discoveries are evaluated on the basis of current outlook conditions.
4. Discoveries that, on evaluation, satisfy minimum conditions of size and profitability are considered to be economic deposits.
5. Cash flow characteristics of the development and production phases of all economic deposits are averaged.
6. Total exploration expenditures, which cannot in general be directly associated with the economic discoveries, are prorated across all economic deposits evaluated.
7. The estimate for the exploration phase is integrated with the average characteristics for the development and production phases to portray the time distribution of average costs and revenues for an economic deposit from the start of exploration to the end of production.
8. Several expected value criteria and risk measures, defined above, are derived from the assessments. These indicators reflect the potential value of mineral exploration.

More specifically, the development and production phase characteristics for each of the possible economic discoveries (step 2, above) are evaluated (step 3), as shown in Figure 1.3, by combining general market estimates of metal prices and smelter payments with estimates for individual deposits of the following: recoverable ore reserves; mill recovery factors; a stripping ratio for open pits; mine and mill capacities; capital costs, including the working capital requirement; the length of the preproduction development period; and operating costs. These estimates, based on the actual historical record, attempt to portray how each deposit would look today if it was awaiting development. A number of measures of economic worth are derived from the resulting cash flow distributions, including the total sales revenue generated and the rate of return. Those discoveries that satisfy minimum conditions for total revenue (size) and rate of return (profitability) are deemed to be economic (step 4). The cash flow estimates for all economic deposits are then averaged (step 5), resulting in a time distribution of average cash flows

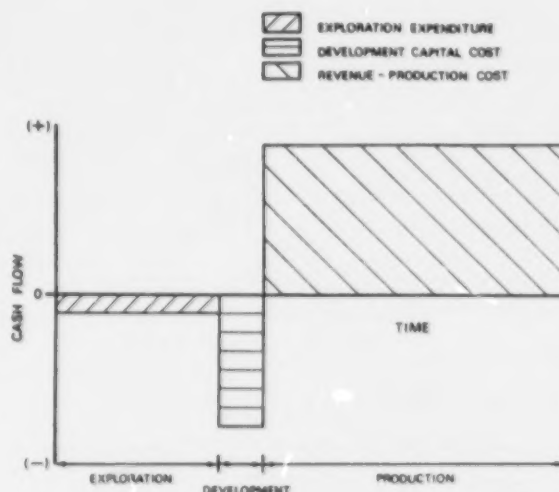


Figure 1.3. Methodology for assessing the potential value of exploration.

for the development and production phases of the mineral supply process.

With respect to appraisal of the exploration phase (step 6), the total exploration expenditure estimate (step 1) is divided by the number of economic deposits assessed (step 4) to determine the average exploration expenditure required to find and delineate an economic deposit. To evaluate the average exploration time that would be needed to make an economic discovery, this average exploration expenditure is then divided by an assumed most-efficient annual exploration budget rate. These estimates for the exploration phase are then integrated with the appraisals for the development and production phases.

As portrayed in Figure 1.3, the end result of this evaluation process is an assessment of the time distribution of average cash flows for an economic deposit over the entire mineral supply process (step 7). This is used to appraise the economics of mineral exploration in terms of the expected value and risk criteria previously discussed.

KEY EXPLORATION CHARACTERISTICS

The examples used in this and the following sections draw on empirical work carried out in Canada and Australia from 1970. The studies from which these illustrations are taken (listed in the Bibliography), carried out over a 15-year period, embody a wide range of terms of reference, data bases, and assumptions, including metal price and exchange rate projections. Thus, the examples are in the nature of vignettes which, although sharing a common methodology, unfortunately cannot be integrated into a

more comprehensive whole. To standardize the illustrative results, all money values have been converted to constant 1985 Canadian dollars.

DIRECT COST OF SUCCESS

A continually asked question is — how much does it cost, on average, to find and delineate an economic mineral deposit (E)?

1. \$38 million; for base-metal exploration in Canada during the 1946 to 1977 period
2. \$50 million; for metal exploration in Australia during the period 1955 to 1978, including an average cost of \$111 million for an economic base-metal discovery, and \$63 million for an economic gold discovery
3. \$25 million; for gold exploration in Canada during the 1946 to 1985 period.

Average discovery costs are shown to vary significantly, even over long historical time frames and among broad exploration environments. These variations are mainly attributable either to differences in endowment characteristics or to differences in exploration difficulty arising from variations in near-surface cover conditions.

These illustrative costs of exploration success represent direct expenditures, making no allowance for exploration's up-front position in the mineral supply process.

THE TIME COST OF EXPLORATION

The most expensive aspect of mineral exploration is not the direct cost of discovering an economic deposit. Rather, the most costly feature is the time value difference between when exploration funds are invested and when the recovery and sale of mineral products from the resulting economic discovery actually take place. The time-adjusted cost of exploration success is typically several times the direct unaccumulated cost.

1. Consider the case of base-metal exploration in Canada during the 1951 to 1974 period. The direct cost of discovering an economic deposit is found to represent 2.6 percent of the associated revenue generated over the deposit's productive life. However, the time-adjusted exploration cost represents 10.2 percent of total revenue.
2. In the case of metal exploration in Australia during the period 1955 to 1978, the direct cost of an economic discovery accounted for 3.1 percent of the total revenue subsequently generated. However, the time-adjusted exploration cost is equivalent to 28.8 percent of the associated revenue produced over the deposit's operating life.
3. Finally, consider the case of gold exploration in Canada during the 1946 to 1985 period. The average cost of finding and delineating an eco-

nomic deposit is assessed to be \$25 million. Expressed another way, this direct cost of exploration success represents \$33 per ounce of recoverable gold discovered and delineated in the associated economic deposit. Assuming a 10 percent minimum return requirement on exploration funds, a \$5 million annual exploration budget, and a 3-year mine development period, the time-adjusted gold discovery cost is \$111 per ounce or, in other words, more than three times the direct cost.

The high time cost of mineral exploration is attributable to the typically long exploration time frame and its up-front position in the mineral supply process. The economic evaluation of exploration must incorporate this important cost.

DISCOVERY RISK AND ITS PRACTICAL IMPLICATION

The average exploration expenditure required to find and delineate an economic deposit (E) is not monolithic. It comprises many relatively modest investments to discover mineral occurrences (C), each of which has only a small chance (p) of proving to be an economic mineral deposit. In other words, a high discovery risk (p) typifies exploration success.

1. $C = \$683\,000$, $p = .019$; for base-metal exploration in the Canadian Shield, 1951 to 1974
2. $C = \$190\,000$, $p = .0046$; for nickel sulphide exploration in Western Australia, 1955 to 1972
3. $C = \$518\,000$, $p = .0032$; for Paleozoic base-metal exploration in eastern Australia, 1955 to 1972

The practical implication of the high discovery risk which characterizes mineral exploration is that there is a large difference between the average expenditure required to find and delineate an economic deposit (E), and the level of funding required to ensure success (A). For example, with respect to each of the above illustrations, consider the exploration funds required to be 90 percent sure of discovering at least one economic deposit.

1. $E = \$36$ million, $A = \$83$ million; for base-metal exploration in the Canadian Shield, 1951 to 1974
2. $E = \$41$ million, $A = \$95$ million; for nickel sulphide exploration in Western Australia, 1955 to 1972
3. $E = \$162$ million, $A = \$372$ million; for Paleozoic base-metal exploration in eastern Australia, 1955 to 1972

The very substantial levels of exploration investment needed to ensure success are a consequence of the high discovery risk which characterizes the search process. An understanding of the required level of funding is pertinent to exploration planning. For example, it would lead us to question the practicality of exploring for Paleozoic base-metal deposits

in eastern Australia. More generally, these funding requirements demonstrate that a strong persistent commitment, from the board of directors and chief executive officer on down, is required for success in mineral exploration.

VARIABILITY OF RETURNS AMONG ECONOMIC DISCOVERIES

One of the fundamental risks in mineral exploration is the variability of the return, given the discovery of an economic deposit. As a consequence of the diversity in tonnage, grade, and other geological characteristics among economic deposits, there is typically a wide range of possible returns distributed around the average or mean return value.

For example, consider the return characteristics for 129 economic metal deposits discovered in Australia to 1978. The following return parameters are utilized:

1. total revenue, evaluated at the mine site, reflecting deposit size
2. rate of return, indicating the profitability of an economic deposit
3. net present value at 10 percent, expressed as a discounted value at the start of development, combining the size and profitability indicators in a single measure

The average return characteristics for the 129 deposits evaluated to be economic are:

1. total revenue, \$1376 million
2. rate of return, 41 percent
3. net present value, \$187 million

To illustrate the variability of return characteristics among the economic deposits discovered, key statistics from the cumulative probability distributions of total revenue, rate of return and net present value for the 129 economic deposits are presented in

TABLE 1.3. KEY STATISTICS OF RETURN CHARACTERISTICS FROM CUMULATIVE DISTRIBUTIONS: 129 ECONOMIC METAL DEPOSITS IN AUSTRALIA.

Key Statistic	Total Revenue (\$ million)	Rate of Return (percent)	Net Present Value (\$ million)
Upper Decile	3194	76	444
Upper Quartile	658	50	132
Mean (Average)	1376	41	187
Median	246	34	41
Lower Quartile	110	21	13
Lower Decile	77	14	4

Table 1.3. The cumulative distribution for net present value is shown in Figure 1.4.

Note that the size (total revenue) distribution for the economic deposits is more variable and much more skewed than the profitability (rate of return) distribution.

With respect to the net present value results, the mean or average potential value for the 129 economic deposits is \$147 million as previously indicated. The variability of the return, given an economic discovery, is illustrated by the more than one-hundred-fold difference in value between the lower-decile and upper-decile economic deposits (\$4 million and \$444 million, respectively).

The net present value distribution is also highly skewed. There are many low-value economic discoveries and relatively few of extremely high value. Thus, the mean value of the economic discoveries (\$187 million) is significantly higher than the value of the upper-quartile deposit (\$132 million), and more than four times greater than the median or middle value of the distribution (\$41 million).

Figure 1.4 shows that, given the discovery of an economic deposit, there is about an 80 percent chance that it will yield a lower-than-average re-

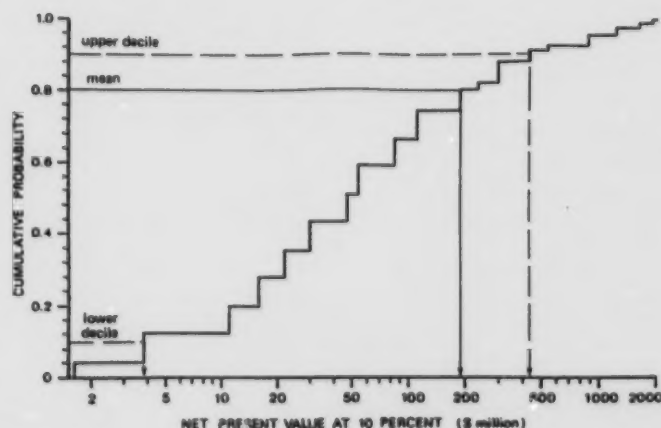


Figure 1.4. Cumulative probability distribution of net present value: 129 economic metal deposits in Australia.

turn. On the other hand, there is a 20 percent chance that an economic discovery will yield an above-average return. There is even a small but significant possibility of a multi-billion dollar discovery.

With respect to the formulation of mineral policy in government, the important message that these return results convey is that there is no such thing as a "typical deposit". Thus, flexibility is required in government policies to equitably and efficiently accommodate the wide range of returns inherent in mining.

THE MULTI-BILLION DOLLAR DISCOVERY

The variable and skewed nature of the return distributions for economic deposits, shown in the previous section, is attributable in part to the presence of a very few elephantine discoveries. These exceptional creatures have a profound effect on the economics of mineral exploration, such as:

1. the influence of the Kidd Creek deposit on the economics of base-metal exploration in Canada during the 1951 to 1974 period. The expected rate of return of exploration for Canada and Ontario with and without the Kidd Creek discovery are shown in Table 1.4.
2. the effect of the Olympic Dam discovery on the economics of metal exploration in Australia during the period 1955 to 1978. The expected rates of return for metal exploration overall, base-metal exploration, and Proterozoic base-metal exploration, with and without Olympic Dam, are presented in Table 1.5.
3. the influence of Hemlo on the economics of gold exploration in Canada during the 1946 to 1985 period. Time-adjusted gold exploration costs per ounce discovered and delineated in economic deposits for Canada and Ontario, with and without the Hemlo discovery, are shown in Table 1.6.

These illustrative results indicate that Kidd Creek, Olympic Dam, and Hemlo, three deposits among two or three hundred economic discoveries, represent a substantial part of the economic mineral potential in Canada and Australia. If these very rare deposits did not occur, the economics of mineral exploration would be impoverished.

The possibility that any exploration program can lead to one of these multi-billion dollar discoveries, although extremely improbable, is no doubt a great motivator in mineral exploration. Such a giant target likely carries weight in exploration decisions beyond its actual numerical contribution to the expected value measures.

EXPLORATION DYNAMICS

For both corporate planning and government policy purposes, it is vital to endeavour to discern time

trends in mineral exploration economics. According to the methodology adopted, these dynamic changes represent the economic consequences of trends in the geological characteristics of mineral resources. In seeking explanations for observed changes over time, the two main geological components — exploration expenditures, and the quality of mineral resources discovered — should be examined⁴.

To illustrate, consider the case of base-metal exploration in Canada during the 1946 to 1977 period. Time trend results are presented in Table 1.7, relative to the overall 1946 to 1977 period averages.

Expected Value Overview

The economic discovery rate appears to have held up well, increasing from the late-1940s to the mid-1950s and then remaining more or less constant. This roughly corresponds to the pattern of exploration expenditures.

It is difficult to discern time trends in the expected value indicators. A comparison of results between the two 16-year intervals suggests that while the profitability of base-metal exploration has tended to be maintained, as indicated by the expected rate of return, the average size of the economic deposits discovered has increased significantly, as reflected by the higher expected value per

⁴ Trends in exploration expenditures reflect the interplay of four dynamic elements:

- changing rates of economic discovery
- depletion effects in terms of increasing exploration difficulty
- real changes in the costs of labour and inter-industry inputs to exploration
- advances in geological concepts and exploration technology in terms of lower discovery costs

Changes in the quality of mineral resources are the resultant of two dynamic elements:

- depletion effects in terms of lower-quality economic discoveries
- advances in geological concepts and exploration technology embodied in the geological characteristics of discoveries

The quality of mineral resources has a number of facets, including:

- deposit size
- geological grade
- geographical location
- ore width
- depth below surface
- mineralogical complexity
- geotechnical properties

Deposit quality affects the selection of mining and processing methods, recoverable ore reserves, mineral processing recoveries, stripping ratio, scale of operation, sales revenues, and capital and operating costs. Thus, the quality of mineral resources is a critical aspect of exploration economics.

TABLE 1.4. EFFECT OF THE KIDD CREEK DEPOSIT ON THE ECONOMICS OF BASE METAL EXPLORATION IN CANADA, 1951-74.

	Expected Rate of Return (percent)	
	With Kidd Creek	Without Kidd Creek
Canada	16	14
Ontario	21	13

TABLE 1.5. EFFECT OF THE OLYMPIC DAM DEPOSIT ON THE ECONOMICS OF METAL EXPLORATION IN AUSTRALIA, 1955-78.

	Expected Rate of Return (percent)	
	With Olympic Dam	Without Olympic Dam
Metals	11	9
Base Metals	8	5
Proterozoic Base Metals	11	6

TABLE 1.6. EFFECT OF THE HEMLO DEPOSIT ON THE ECONOMICS OF GOLD EXPLORATION IN CANADA, 1946-85.

	Time-Adjusted Exploration Cost (\$ per ounce)	
	With Hemlo	Without Hemlo
Canada, 1946-85 period	111	143
Ontario, 1946-85 period	118	392
Canada, 1981-85 interval	156	279

TABLE 1.7. TIME TRENDS IN BASE-METAL EXPLORATION ECONOMICS, CANADA, 1946-77.

	Total Exploration Expenditures (\$ million)	Number of Economic Discoveries	Average Discounted Exploration Expenditures (E, \$ million)	Average Discounted Return (R, \$ million)	Expected Value per Economic Discovery (EV, \$ million)	Expected Rate of Return (percent)
1946-77 period	3705	96	27	144	117	18
By time interval:						
1946-61	1175	42	21	109	88	18
1962-77	2530	54	31	159	128	18
1946-53	272	16	14	212	198	27
1954-61	903	26	24	61	37	13
1962-69	1296	27	31	216	185	20
1970-77	1234	27	30	99	69	14

economic discovery during the most recent 1962 to 1977 interval.

Results for the four 8-year time intervals are more erratic. A severe deterioration in productivity is evident from 1946 to 1953, to 1954 to 1961, coming back to above-period values for the 1962 to 1969 interval, before falling off once again during 1970 to 1977. The evidence presented here points to a possible decline in the expected rate of return over the study period.

These results illustrate that changes in exploration economics are neither gradual or systematic. Despite the application of scientific concepts and increasingly sophisticated exploration technology, there appears to be great fluctuations in the economics of mineral exploration with time. Thus, long-term trends are not easy to detect.

The Exploration Expenditure Component

Exploration activity during the study period grew from a relatively small base, the 1946 to 1953 interval accounting for only seven percent of total exploration expenditures for the period (see Table 1.7). Average exploration expenditures per economic discovery increased significantly from the first to the second half of the study period. Economic discovery costs almost doubled from 1946 to 1953, to 1954 to 1961, followed by a more modest rise to the 1962 to 1969 interval. However, average exploration expenditures do not appear to have increased since the early 1960s.

Quality of Mineral Deposits Discovered

Significant points arising from the time trend in the average return associated with an economic deposit are:

1. Average return characteristics deteriorate from 1946 to 1953 to 1954 to 1961, improve for the 1962 to 1969 interval, and then fall off once again for the most recent 1970 to 1977 interval. No systematic overall time trend is apparent.

2. The serious decline in return characteristics for the 1954 to 1961 interval, symptomatic of depletion effects, may have resulted from more intensive application of an exploration technology that was essentially unchanged from that used in the 1946 to 1953 interval to lower priority targets.
3. The influence of large low-grade economic porphyry deposits is mainly concentrated in the interval 1962 to 1969. This is illustrated by the large average return for the interval. The high expected values for 1962 to 1969 appear to contradict the notion that porphyry deposits are not generally very profitable. However, other high-grade and more profitable discoveries are likely influential here, such as the Kidd Creek discovery in 1963 and the Ruttan deposit discovered in 1969.

No systematic trend is apparent in the quality of base-metal resources discovered during the 1946 to 1977 period. Available evidence does not support the contention that the quality of Canada's base-metal resources has deteriorated with time.

GEOGRAPHICAL VARIABILITY

Two examples are provided here of exploration planning issues which concern geographical variability in the economic characteristics of mineral exploration.

The Question of Remote Area Exploration

Conventional wisdom suggests that mineral exploration, development and production in remote areas is more costly and, therefore, less economic than in more-favourably located regions. Is this hypothesis necessarily correct?

The supposition has been examined with particular reference to the economics of base-metal exploration in the northern Canadian territories relative to the more established mining areas in the provinces. Despite the adverse economic effects of the higher remoteness costs associated with mining in the north, base-metal exploration economics in the northern territories is shown to be more attractive than in southern Canada. There are two main reasons for this unexpected result.

First, the average exploration expenditure required to find and delineate an economic deposit in the north, \$13 million, is found to be much lower than the \$46 million average discovery cost in the southern provinces. Three reasons for this comparative result are suggested:

1. Deposits are easier to find in the territories because there is better bedrock exposure and because most of the area lies above the treeline.
2. Exploration is more efficient in the north which accounts for 10 percent of Canada-wide exploration expenditures spread over 39 percent of its

landmass, implying a smaller number of active companies and less re-exploration and overlap.

3. Depletion effects in the established mining districts of southern Canada in terms of fewer undiscovered deposits and deeper, more costly exploration programs, are resulting from a prolonged, intensive exploration history.

Second, despite the high development and production costs associated with remote deposit locations in the north, the average return characteristics for economic discoveries in northern and southern Canada are found to be remarkably similar. The relative closeness to surface of the northern deposits enable the applications of mining methods which are sufficiently lower in cost compared to the typically deep underground mines in the south to offset the higher remoteness costs associated with their location. An examination of the changing mixture of discovery methods employed over time and between the two areas shows that base-metal exploration and discovery in northern Canada is at a much less mature stage, lagging behind the south by at least 20 years. Thus, the quality of deposits found to date in the north appear to be comparable to the endowment characteristics of pre-1946 economic discoveries in the south.

These case study results demonstrate that more remote does not necessarily mean less economic.

Australia or Canada?

Since the illustrations used in this paper have been drawn from Australian and Canadian experiences, it may be of interest to compare mineral exploration economics in the two countries. At present, because of data base restrictions, this can only be partially done. A comparison has been made of the economics of base-metal exploration in Australia during the period 1955 to 1978 with similar assessments made in Canada for the 1946 to 1977 period. Summary results are presented in Table 1.8. The main finding arising from these results is that the economics of base-metal exploration in Australia is quite different from the Canadian experience.

While the economics of base-metal exploration in Australia has been somewhat marginal, decidedly positive expected values have been realized in Canada. The level of base-metal exploration expenditures in Canada over the study period is found to be almost three times that of Australia, but the resulting number of economic discoveries assessed is more than six times greater. This evidence indicates that an economic base-metal deposit in Australia costs twice as much and takes twice as long to find and delineate as one in Canada. On the other hand, the economic base-metal deposits which have been discovered in Australia are typically twice as large as in Canada.

Mineral exploration in Australia and Canada utilizes comparable geological expertise, exploration

TABLE 1.8. BASE-METAL EXPLORATION ECONOMICS IN AUSTRALIA AND CANADA: EXPECTED VALUES FOR AN ECONOMIC DEPOSIT.

	Australia	Canada
Total exploration expenditures (\$ million)	1398	3686
Number of economic discoveries	17	106
Time periods (years):		
Exploration	14	6
Development (maximum)	5	5
Production (maximum)	43	48
Undiscounted Values (\$ million):		
Revenue	3411	1696
Exploration expenditure	82	35
Development capital cost	113	99
Production cost	1510	613
Cash flow	1706	949
Discounted Values (\$ million):		
Average exploration expenditures (E)	49	27
Average return (R)	128	188
Expected value (EV)	79	161
Expected rate of return (percent)	12	22

technology, and organizational efficiency. Thus, the striking overall differences in exploration results may be due to one of two possible reasons. First, there may be a fundamental difference in base-metal endowment characteristics between the two countries, with fewer, larger deposits actually occurring in Australia. Second, base-metal exploration in Australia may be much more difficult and less effective than in Canada, reflecting the productivity of geophysical exploration in glaciated Canadian environments as compared to the problem of detecting medium- and small-sized deposits beneath the deeply weathered, near-surface zone which blankets most of Australia.

More detailed study results show that the return characteristics of base-metal discoveries in the Appalachian region of Canada are similar to those of discoveries made in similar Paleozoic rocks of eastern Australia. Furthermore, it is only in the Paleozoic environment of Australia that the weathered zone has been removed so that here base-metal exploration in both countries has probably been equally effective. This evidence indicates that the overall differences in exploration costs and the size of economic discoveries in the two countries is the result of more effective exploration in Canada to date. This further suggests that an undiscovered population of small- and medium-sized base-metal deposits under the complex weathered zone which covers most of Australia awaits discovery by more advanced exploration technology.

THE BENEFITS OF EXERCISING CONTROL

The foregoing illustrations of key exploration characteristics average together a wide range of individ-

ual company performances which may generally be grouped into two categories. Probably at least 80 percent of the companies exploring in particular exploration environments are never successful. When the costs associated with these failures are subtracted out of the exploration expenditure totals, a rich cost-risk-reward relationship remains for the few successful companies.

Although luck may be a short-term determinant of exploration success, the companies which perform well above average in the longer term are the teams which are most successfully exercising control over the mineral exploration process. The examples which follow illustrate the results of judiciously applying selectivity and control in exploration. In so doing, they indicate the opportunity which is available to all companies to focus exploration in a way which encourages success.

TWO EARLY EXAMPLES

Initial work on exploration economics in Australia, carried out in 1973 to 1974, documented experience during the 1955 to 1972 period. Overall findings indicated that exploration in the base-metal and nickel sulphide environments were characterized by negative expected values, i.e. more exploration expenditures going into the ground in time adjusted terms than the returns coming out from economic discoveries. The results were as follows.

Paleozoic base-metal exploration: \$1.85 of exploration expenditure per \$1 of return.

Precambrian base-metal exploration: \$1.36 of exploration expenditure per \$1 of return.

Nickel sulphide exploration: \$1.67 of exploration expenditure per \$1 of return.

Within this dismal overall picture, mainly reflecting the high costs associated with an initial take-

off stage of mineral exploration, two corporate performances stood out as being particularly successful — Western Mining Corporation (WMC) in the nickel sulphide environment, and Peko-Wallsend in the Precambrian base-metal environment.

In the nickel sulphide environment, WMC incurred eight percent of the total exploration expenditures, discovered 27 percent of the economic deposits, and realized 59 percent of the aggregate return from the economic discoveries. Similarly, in the Precambrian base-metal environment, Peko-Wallsend incurred seven percent of the total exploration expenditures, discovered 44 percent of the economic deposits, and realized 42 percent of the aggregate return from the economic discoveries.

In environments which are characterized by negative overall expected values, the selection of exploration programs of exceptional merit is a necessary condition for long-term exploration success. Exploration was in fact a highly profitable endeavour for WMC and Peko-Wallsend despite the negative overall expected values which characterized the nickel sulphide and Precambrian base-metal environments during this boom period. These performances were linked to persistent long-term exploration strategies based on the application of superior skills and selectivity.

WESTERN MINING CORPORATION IN AUSTRALIA

More recently, an assessment has been made of the exploration performance of Western Mining Corporation (WMC) during the 1955 to 1978 period in the base-metal, gold, nickel sulphide, and tin-tungsten environments of Australia.

WMC exploration expenditures in these environments during the period 1955 to 1978 total approximately \$105 million, representing about seven percent of the expenditures incurred by all companies. Of this total, 55 percent has been spent on exploration for nickel sulphide deposits, 35 percent for base metals, eight percent for gold, and two percent for tin-tungsten deposits.

This WMC exploration investment resulted in the discovery of 28 possible economic deposits. These deposits represent 28 percent of the individual discoveries, and 45 percent of the multi-deposit mineral fields, made by all companies. The favourable overall WMC relationship between relative proportions of exploration expenditures incurred and number of discoveries realized is also evident in all four of the specific environments studied.

The overall productivity of WMC exploration is reflected by an expected rate of return on investment of 26 percent, as compared to seven percent

for the combined results of other companies' exploration efforts.

The expected rate of return on WMC exploration varies from 20 percent in the base-metal environment, to 24 percent for gold exploration, and 26 percent in the nickel sulphide environment; as compared to five percent, two percent, and five percent respectively for the other participants taken together. There is insufficient WMC exploration experience in the tin-tungsten environment to provide a meaningful result.

Over the period of study, there has been no noticeable deterioration in the economics of WMC exploration. Exploration performance, even under pessimistic metal price assumptions, remains decidedly economic.

WMC's exploration performance to date in the base-metal environment is essentially dependent on the Olympic Dam discovery. While Olympic Dam has a strong positive influence on expected values for WMC exploration Australia-wide, and for the most recent time interval examined (1971 to 1978), these situations are quite economic even if Olympic Dam is hypothetically removed from the discovery record.

With respect to organizational risk, the exploration funds required to insure the discovery of at least one economic deposit have been assessed. For WMC, the required funding level varies from \$13 million in the gold environment, to \$122 million in the base-metal environment, as compared to a range of \$62 million to \$267 million for other companies active in these environments.

Aside from the Olympic Dam deposit, WMC's economic discoveries have been smaller and less profitable than average. Thus, the assessed superiority of WMC exploration performance cannot generally be attributed to better return characteristics for its discoveries.

Study results demonstrate that while the economics of mineral exploration in Australia during the 1955 to 1978 period has been marginal overall and uneconomic for other companies taken as a group, a very handsome economic payoff has been realized from WMC exploration activities. There are two main reasons for this outstanding performance.

1. The extremely large size of the Olympic Dam deposit coupled with its average profitability:

Under the assumed evaluation conditions, the estimated rate of return for the Olympic Dam deposit is close to the average for all economic deposits. However, the total revenue indicated for this deposit is more than 20 times greater than the average for all economic deposits, and its net present value is about 14 times higher than average. Thus, the estimated dollar value return from Olympic Dam has a strong influence

on the average return characteristics associated with WMC exploration performance.

2. The cost effectiveness of WMC exploration:

Overall expected value assessments indicate that, on average, an exploration expenditure of \$8 million over about a 3-year period is required for WMC to discover an economic deposit. This compares with an average exploration expenditure of \$54 million over 22 years for all other companies. The economy of WMC exploration in terms of both cost and time is the single most important reason for the attractive corporate results obtained. The high level of exploration expenditures included in the study suggests that luck cannot be primarily responsible for this exploration performance. Rather, the cost effectiveness of WMC exploration must be attributable to some combination of superior geological concepts, exploration technology, and organizational motivation and efficiency.

TEXASGULF AND KIDD CREEK MINES IN CANADA

An economic assessment has also been made of the exploration performance of Texasgulf and Kidd Creek Mines (KCM). The study embodies all KCM activities in Canada during the 1946 to 1984 period. The central part of this effort, exploration for base metals during the period 1946 to 1977, is selected here to compare KCM performance with average exploration results for all companies in Canada (including KCM) and other companies (excluding KCM). This restriction was necessary because of the limits of the overall Canadian data base at the time the study was conducted.

Exploration for base metals during the 1946 to 1977 period accounts for \$77 million (or 58 percent) of total KCM expenditures. Correspondingly, 12 (or 63 percent) of the significant KCM finds are base-metal deposits discovered in 1946 to 1977. Compared to overall base-metal exploration activity in Canada, an above-average performance is indicated. While KCM incurred less than three percent of total Canadian base-metal exploration expenditures, the company discovered more than five percent of the possible economic deposits.

The comparative expected value examination demonstrates that while base-metal exploration in Canada during the 1946 to 1977 period has been an uneconomic endeavour overall, given the assumed evaluation conditions for this particular case study, a handsome payoff has been realized from KCM exploration activities. For example, the expected rate of return on investment is shown to be eight percent for all companies, seven percent on average for the other companies, and 30 percent for KCM. As in the Western Mining case, there are two main reasons for this exceptional performance:

1. the cost effectiveness of KCM exploration
2. the superior average returns associated with the economic deposits found

Other highlights of this comparative aspect of the study are:

1. The superior KCM performance holds for wide ranges of metal prices, minimum acceptable size and profitability conditions, and annual exploration budgets considered.
2. Under pessimistic lower-limit metal price projections, the Kidd Creek deposit would be the only one of the 232 base-metal discoveries evaluated in Canada which would justify development.
3. If the Kidd Creek deposit is hypothetically removed from the discovery list, KCM exploration would still be economically justified and significantly more productive than the collective performance of the other companies.
4. Considering discovery risk, the level of exploration funds required by KCM to ensure success is less than half the amount which would typically be needed by the other companies.

The return characteristics of the three economic KCM base-metal discoveries — Izok, Kidd Creek, and Nanisivik — are ranked in league with returns for the 48 economic deposits assessed in Canada. The Kidd Creek deposit is evaluated as the single best discovery in terms of total revenue generated, net present value, and rate of return. On the other hand, the return characteristics of the Nanisivik deposit are shown to be relatively marginal. Based on the anticipated long-term economic conditions adopted in the study, the Izok deposit ranks high in this league of economic discoveries.

The bottom line of this study is that the exploration performance of Texasgulf and Kidd Creek Mines in Canada is of a high quality and has the potential to substantially increase the net value or wealth available both to the company and to society. Compared to the combined experience of other companies exploring in Canada, study results show that this performance is outstanding.

INGREDIENTS OF EXPLORATION SUCCESS

One basic question remains — how can we create, nurture, and sustain an exploration team which is capable of performing well above average?

In mineral exploration, most companies are never successful. What can be learned from these many mistaken endeavours? Some commonly encountered symptoms of failure in mineral exploration are:

1. lack of persistence, arising from inability to understand the realities and strategic role of mineral exploration at the board level

2. bureaucratic, layered, committee-managed style of exploration organization
3. separation of decision-making power from the knowledge base required to take informed decisions
4. plan exploration on a conventional wisdom, herd instinct or, in other words, do what everyone else is doing
5. counterproductive relationship between head of office management and the exploration team
6. concept of exploration as a game of chance with luck being the main determinant of success
7. idea that the company will be successful if it simply throws enough money at exploration
8. government policies which provide incentives for exploration expenditures per se rather than successful exploration

Conversely, the case study results which have been presented lead us to more generally consider the ingredients of exploration success. It is suggested here that there are five main ingredients:

1. Superior Scientific and Technical Skills

To be successful in mineral exploration, a company must be prepared to invest in and develop the human resources required to perform well above average. There must be a willingness and genuine interest to test new geoscience ideas and ore deposit models. A process of continuing professional education is required including in-house discussion, short courses and seminars, and, most importantly, a graduate study leave program. The cost of human resource development should be an integral part of the exploration budget.

2. Chain of Confidence Within the Company

Does the company believe from its board of directors and chief executive officer on down that successful mineral exploration is the number one way that the company is going to survive, profit, and grow in the longer term? As Roy Woodall (Woodall, Paper 6, this volume) highlights, a chain of confidence is required within the company running from the directors to the field geologists, and from the field geologists to the directors. Management must be willing to decentralize exploration responsibilities so there is an identity between knowledge and decision-making power.

3. "Hunting Band" Size and Type of Exploration Team

The exploration team should have an entrepreneurial-type of professional and economic motivation, dedicated to the discovery of economic mineral deposits. A critical mass of five to eight geologists — "hunting band" size — with an annual budget of \$1.5 million to \$4.0

million appears to be the most efficient and effective, retaining the characteristics of an entrepreneurial organization while avoiding the weakness of a bureaucracy.

4. Economic Guidelines

An economic overlay is essential to translate the scientific-technical basis for exploration success into economic criteria that can be related to corporate objectives. Economic guidelines are required for exploration planning from the initial formulation of strategies to the evaluation of ongoing exploration programs and projects. Economic criteria underly the phased approach to exploration, and provide the focus for encouraging exploration success.

5. Positive Government Policy Environment

To motivate successful exploration, government has to provide an efficient and workable mining code and mineral leasing system. Policies should stimulate competition through minimum work commitments, annual rentals, and periodic reduction of areas held. In endeavouring to provide the right mix of economic incentives, the high risk nature of mineral exploration has to be taken into account. Accordingly, it is imperative that government policies encourage exploration success rather than exploration expenditures per se.

These ingredients of exploration success appear to be both clear and simple, really only common sense. Why then are they so rarely encountered in the real world?

CONCLUSION

The paper illustrates the economic characteristics of mineral exploration. These characteristics provide mining companies with an unrivaled opportunity to focus their exploration activities to encourage success. Several corporate case studies are used to document the benefits to be derived from the judicious application of selectivity and control in exploration. While the ingredients of exploration success appear straightforward, symptoms of exploration failure are more commonly encountered. There is great scope for improving the economic performance of mineral exploration.

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APPENDIX A

ILLUSTRATIVE EXPLORATION PROGRAM

The case study described here is based on a typical exploration program for volcanic-associated massive sulphide deposits in the shield region of Canada. It is assumed that this environment has been selected by a mining company as being favourable based on geologic, market, technologic, economic, legislative, and organizational factors. All money values are expressed in constant 1985 Canadian dollars.

PROGRAM DEFINITION

The illustrative exploration program progresses through five stages as follows.

1. Area Selection Stage

- starting point is the exploration environment of interest, which may vary in size from several tens of thousands of square kilometres to several hundreds of thousands of square kilometres

EXPLORATION '87 PROCEEDINGS
THE ROLE OF EXPLORATION IN RESOURCE DEVELOPMENT

- consists of compilation of existing data, use of scientific concepts and ore deposit models, and field investigation

- results in the definition of favourable areas of variable size, averaging 500 km²

- average cost of \$20 000 for each area selected

2. Airborne Reconnaissance Stage

- starting point is a favourable 500 km² area

- consists of:

- electromagnetic and magnetic surveys

- 300 m spacing of lines, 1800 line-km flown, cost of \$40 per km

- results in the definition of priority conductors

- areas flown vary from low intensity to high intensity and, consequently, the resulting number of priority conductors vary, normally within the range of 20 to 40, and averaging 30 for a 500 km² area. Each priority conductor covers an area of 1 km²

3. Ground Follow-Up Stage

- starting point is the 30 priority conductors selected

- consists of:

- acquisition of mineral rights for each conductor, 10 claims at cost of \$150 per claim

- line cutting for each conductor, 10 line-km at cost of \$160 per km

- ground electromagnetic and magnetic surveys for each conductor, 8 line-km at cost of \$270 per km

- grid geological mapping, cost of \$430 per conductor

- results in the definition of drilling targets

- on average, 60% of the conductors examined are selected as initial drilling targets

4. Exploratory Drilling Stage

- starting point is the average of 18 drilling targets selected

First-Stage Drilling

- a single hole is typically drilled on each target, to an average depth of 100 m, at a cost of \$115 per m.

- 95% of the targets drilled are rejected after this first hole.

- 5% of the targets drilled give indications of mineralization of potentially economic grades across mineable widths. These constitute the "discovery of mineral occurrences", and are selected for second-stage drilling.

Second-Stage Drilling

- An average of 4 additional holes are drilled on each target selected at an average cost of \$60 000 per target.

- 20% of the targets drilled give sufficiently encouraging results to justify third-stage drilling.

Third-Stage Drilling

- An average of six additional holes are drilled on each target selected at an average cost of \$105 000 per target.

- 30% of the targets drilled give sufficiently encouraging results to justify delineation drilling.

5. Delineation Drilling Stage

- The purpose of this stage is to provide the basis for initial estimates of tonnage-grade potential for each target selected.

- The cost of delineation drilling varies widely, normally within the range of \$250 000 to \$1 500 000 depending on deposit size and variability, the reliability desired, and the perceived eco-

TABLE 1.9. METHOD FOR AVERAGING COST OF EXPLORING A 500 KM² AREA.

			\$
1.	Area Selection:		20 000
2.	Reconnaissance: 1800(40)		72 000
3.	Follow-Up:		
	acquisition	= 30(10)(150) = 45 000	
	line cutting	= 30(10)(160) = 48 000	
	geophysics	= 30(8)(270) = 65 000	
	geology	= 30(430) = 13 000	
	total	171 000	171 000
4.	Exploratory Drilling:		
	first-stage	= 30(.6)(100)(115) = 207 000	
	second-stage	= 18(.05)(60 000) = 54 000	
	third-stage	= .9(.2)(105 000) = 19 000	
	total	280 000	280 000
5.	Delineation Drilling: .18(.3)(750 000)		41 000
	Typical Program Cost per 500 km ² Area		\$584 000

conomic significance of the drilling results obtained. Average delineation cost of \$750 000 per target selected is assumed.

- One-half of the targets delineated constitute "possible economic discoveries for evaluation", providing justification for pre-feasibility testwork and studies.

- One-third of the targets delineated ultimately prove to be economic mineral deposits.

TYPICAL PROGRAM COST

The typical or average cost of exploring a 500 km² area from selection of the area to delineation drilling (if warranted) is derived as illustrated in Table 1.9.

OTHER ECONOMIC INDICATORS

C = typical or average exploration cost associated with the discovery of a mineral occurrence
= 584 000/0.9 = \$649 000

p = probability of an economic mineral deposit given the discovery of a mineral occurrence
= (.2)(.3)/3 = .020
(alternatively, .018/.9 = .020)

E = average exploration cost required to find and delineate an economic mineral deposit
= 649 000/.020 = \$32.5 million
(alternatively, 584 000/.018 = \$32.5 million)

2. The Future of Mineral Exploration and Mine Development in the Developing Countries

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ABSTRACT

The continued depression of the minerals industry is naturally leading to a greater disparity in exploration expenditure between the "have" and "have not" countries, even with respect to the precious metals. The acquisition as opposed to the exploration route will not drastically change the low level of mine development investment in much of the Third World. The inherent, often real as well as perceived, risks remain.

Given the declining per capita consumption of raw materials, an irreversible shift away from large industrial metal mines is already occurring. In the traditional sense, therefore, there will be a declining need for large-scale exploration programs in many of the developing countries during the foreseeable future. Growing global financial uncertainty will also be an impediment to investment.

The possibilities for finding high-value low tonnage deposits in the developing countries are high and these will need to be developed by whatever means if only to generate foreign exchange. If the international mining community is to survive, and there is no doubt that their expertise is required, then a scaling down of operations is inevitable.

Present working mechanisms, international, bilateral, and often private ventures, are not totally satisfactory for a variety of often debated reasons. These difficulties are summarized. Building on existing arrangements in international institutions, a possibility is examined for developing an internationally guaranteed joint-venture arrangement in an effort to forge a bond between private investors and often skeptical and inexperienced host countries.

INTRODUCTION

An attempt to assess the future of mineral exploration and mining developments in the Third World cannot go much beyond generalities if only because of a very uncertain future, indeed. The situation is different from ten or 15 years ago. Building around the announced plans of the major international mining houses, coupled with analyses of the exploration activities of the United Nations and bilateral programs, major continued growth was predictable. For example, taking copper as typical, the following great and comparatively rich orebodies would have been depicted as well on the way to production — Cerro Colorado and Petaquilla in Panama,

Toromocho, Michiquillay, and Quellavaco in Peru, Los Pelambres and Andocollo in Chile, El Pachon in Argentina, Sar Cheshmeh in Iran, and Saindak in Pakistan. Where do they stand now? Virtually all are as far away from producing ingot as they were a decade ago. Selebi-Pikwe and Ok Tedi have their own present and yet unknown problems.

The continued depression of the industry, probably only temporarily buoyed by recent upward price adjustments, does not auger well for the developing countries. The inherent, often real as well as perceived, risks will remain. Accordingly, there is little scope or reason for case by case, country by country, assessment of possibilities for bringing into production new mineral wealth in developing nations. Increasingly, the dominant factors conditioning mineral investment in many countries are economic and political with the merits of the orebody often running a poor third. Obstacles to mineral development, particularly with respect to the developing countries, have been pragmatically assessed by Carman (1979).

With exploration, the basic consideration is that with most non-fuel minerals, there are sufficient proved reserves to satisfy global needs well into the 21st Century, unless one postulates industrial expansion worldwide approximating that of the glory decades following World War II. On the other hand, should there be appreciable revival of the annual growth rates of the sixties (4.3 percent) and the seventies (5.8 percent), the industry might have its hands full to open up the new mines required and rehabilitate old ones. Unfortunately, however, the main thesis of this paper is that it would be unrealistic to expect a return to "the good old days". Nevertheless, there should be a considerable incidence of exploration bets with the targets being selected minerals and/or high-grade, medium-sized deposits. The move in this direction is already underway in Canada. It could take place in more than a few developing countries under internationally guaranteed joint ventures. Considering that at least 50 percent of future resources occur in the developing countries, the plight is such (Mining Journal 1986) that other means will be found to bring resources into production other than through direct private investment. Scaling down of operations by the international private sector is probable and diversification away from mining using, largely, substantial gold-generated profits may be an unfortunate but viable option for the industry.

NEGATIVE FACTORS

THE DECLINE OF MINERAL VALUES

There is an understandable tendency to view the difficulties of the past few years as simply a reflection of the "boom or bust" nature of the free enterprise system. The extraordinarily strong growth pattern since 1945 has, by its very nature, been interrupted by recessions of relatively short term and mildness. It is therefore understandable that recent hardship has been viewed by too many as simply another manifestation of the cyclical pattern in mineral affairs; it is anything but. Instead, it is part of a trend of long duration. The life history of the demand for any particular mineral closely mirrors that of Man: youth turning into staid middle age and then onto decline. There is ample reason to believe that we are approaching the last stage. This end of an age has been well depicted by Larson *et al.* (1986):

"In recent years there appears to have been a fundamental change in this pattern of growth. In North America, West-

ern Europe and Japan economic expansion continues, but the demand for many basic materials has levelled off. It appears that the industrial countries have reached a turning point. They are now leaving the Era of Materials which spanned the two centuries following the advent of the Industrial Revolution, and are moving into a new era in which the level of materials use will no longer be an important indicator of economic progress."

One could debate the concluding sentence. Nevertheless, the thesis is well-founded. The report shows that the consumption of steel as a unit of GNP peaked in the United States in 1918. Per capita consumption leveled off around 1950 and has been declining since 1972. The same patterns set in progressively later with aluminum, cement, paper, and chlorine. By 1970, all were showing almost static relative growth. There is little on the horizon to suggest reversals of trends.

World production of aluminum and steel on a per capita basis (Figure 2.1) shows that the world as a whole is starting to evince the maturity of the United States. These figures are substantiated by

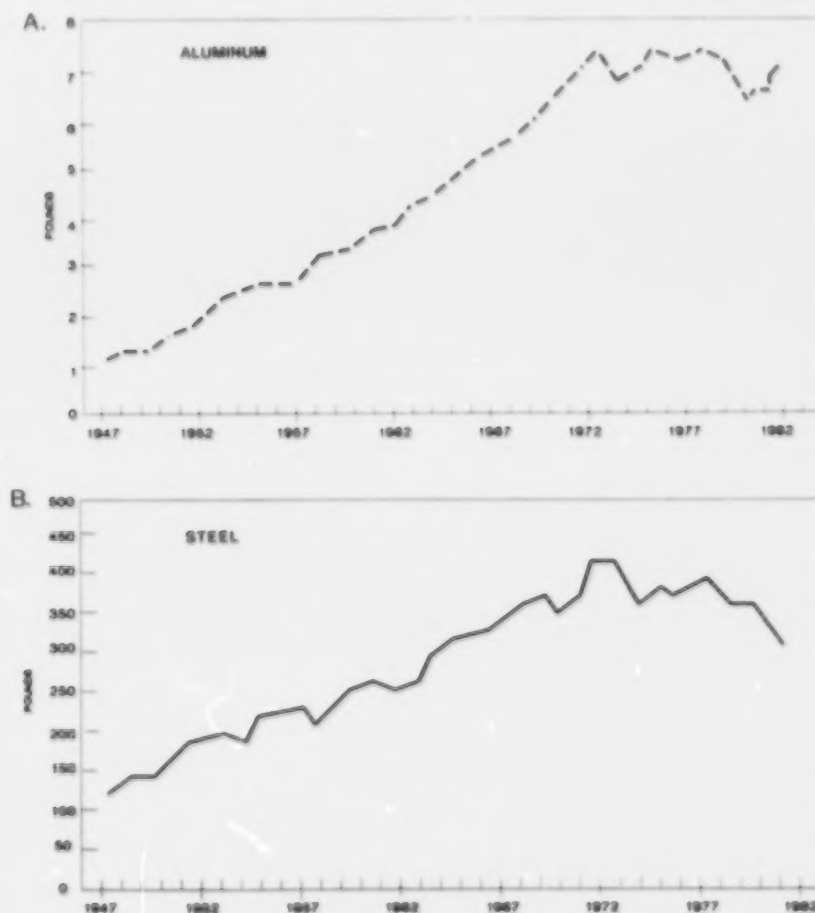


Figure 2.1. World production for aluminum (1947-84) and steel (1947-82) on a per capita basis.

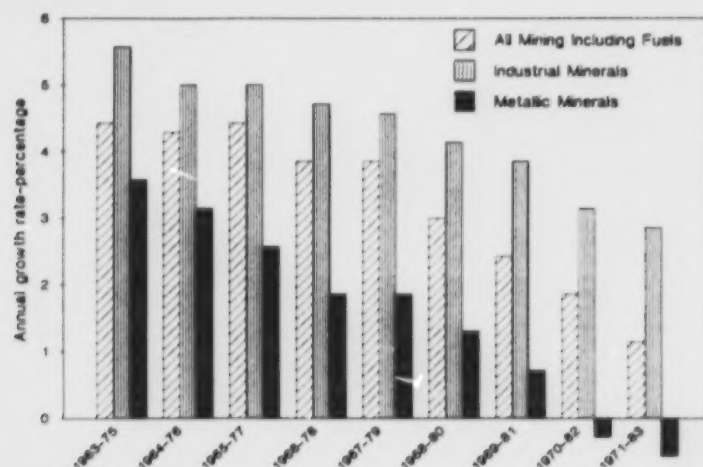


Figure 2.2: The decline of world mining output in terms of growth rates (1963-1983).

Brunner (1985) who also shows the declining intensity of metals use.

The principal focus of most "hard rock" exploration is to discover metallic minerals, the decline in mining output (Figure 2.2) has to be viewed as being particularly chilling. This offers a great deal of support to the analyses of Larson *et al.* (1986).

Pricing History of Base Metals

On the basis that copper, lead, and zinc are reasonably representative of the principal metallics used in industry, Table 2.1 is quite indicative.

It is considered unnecessary to precisely calculate the devaluation of the dollar since the turn of the century. To put the matter in perspective, in 1904, ten cents would buy a flagon of beer requiring two hands for the hoisting plus a free lunch, a Model T sold for less than 200 dollars, and a solid brick house boasting four bedrooms for about 1500 dollars.

In effect, the mining industry of the world has done a splendid job in meeting the World's explosive needs and done so with quite marked reductions in real prices since mass mining of low-grade ores was introduced at Bingham Canyon shortly after the turn of the century. On average, the prices of the

metals listed above were slightly higher in 1975 than in 1986 despite continuous inflation, sometimes in double digits. What lies ahead is not encouraging.

1. An industry which has had an outstanding record throughout most of a very demanding century in regard to ingenuity, technological breakthroughs, and quality management at the operating level, finds itself with its protection against cold winds seriously shredded. The Law of Diminishing Returns has undoubtedly set in with respect to labour productivity, improvement in process, and extraction technology. The investment needed to bring new mines into production has skyrocketed at rates far exceeding those of inflation data published by governments.
2. The collapse of the Tin Council, a model of its kind and about the only one which worked in the metals field, demonstrated that such organizations, valuable though they may be to both consumers and producers, cannot survive prolonged drops in prices in inflationary times. The tin problem alone has caused dramatic problems with traditional mineral-based economies in some countries.
3. A large part of world output of minerals is controlled by hard-pressed governments of the developing world. Such production tends to be quite inelastic, with economic factors often being subordinated to social and foreign exchange considerations. A lot of it constitutes very tough competition indeed, and creates international price ceilings which are hard to pierce.

Other Inhibitors

ECONOMY OF USE

At the beginning of the 19th century, the ratio of weight to power in a locomotive was about 1000 kg

TABLE 2.1: COMPARATIVE PRICING OF COPPER, LEAD, AND ZINC, 1904 TO 1986.

1904 - 1986 Period	Copper	Lead	Zinc
	cents/pound		
1904 - 1913 average	15.4	4.6	5.6
1975 - 1986 average	74.1	30.1	39.0
Percentage increase	381	554	596

per horsepower. With the substitution of steel, plastics, and other light materials for cast iron coupled with constant improvements in design, it was reduced to only 14 kg per horsepower. This may seem to be an extreme example, but is more likely representative of a constant battle fought by competitive industry down through the ages.

SUBSTITUTION

Plastic and ceramic materials continue to replace metals. When was the last time that we can recall a reverse process of importance?

ENVIRONMENTAL

It is well known that there are valid public concerns over such environmental issues as air and water quality and the disposal of hazardous wastes. A comment by Brooks (1973) is relevant:

"Contrary to Conservationist tradition, I see most non-renewable resources as all but continually available over time, whereas the supposedly renewable resources such as air and water are in jeopardy of depletion."

Environmental protection affects the mineral industry, both in direct costs at the mining and refining stages, and may result in the future decreased demand for certain commodities.

A GLOOMY PICTURE

The litany of woe in foregoing sections is well known to all those concerned with the demand for minerals. It has in many ways been reacted to intelligently and effectively through research on downstream product development, marketing strategies, computer technology, and scaling down. The difficult environment has been beneficial in regard to conservation of resources in that many inefficient and wasteful operations have been weeded out.

THE FUTURE

AN OVERVIEW

If the mining industry is to survive and survive through change in a changing world, there appears to be three alternatives. The first would be to maintain the status quo; continue productivity efficiency, develop commodity flexibility (will gold continue to be the bread and butter of such a large part of the industry over the medium term?), concentrate on new investment only in secure risk environments, and, as far as third world investment is concerned, occasionally strike when perceived returns offset perceived political front-end risks. The second alternative would be similar to the first except that major exploration and development work in most of the Third World by the international private mining sector would be virtually curtailed during the next several decades at least. This could well be a necessary, albeit short-sighted, alternative with its correspond-

ing evils; increased output from Third World countries at lower, often subsidized production costs. The third alternative would require an all out effort by the international community joining forces with the private sector, instilling confidence in receptive developing countries and working with them as risk-sharing partners in an open economy. A major benefit of such a scheme and one which is becoming increasingly urgent for the developing world, is the generation of foreign exchange. Let us make no mistake, more than half of the world's mineral resources occur in the Third World. When necessary, these will be developed and will enter the market, often regardless of production economics.

Although not applicable across the board, one of the new scenarios can be demonstrated by the Finnish Outokumpu Oy approach; the purchase of foreign (not Third World) mines to assure supply continuity at, for example, Tara (Ireland), Viscaria (Sweden), as well as ventures in Canada, Australia, Norway, and the USA and withdrawal from Cerro Colorado in Panama. This approach makes sound sense for a company such as Outokumpu as it does for other similarly structured groups, but in the medium-term, there will be a limit to who can acquire what and where at an acceptable price. There are limits to acquisitions. Exploration and new mine development will, therefore, be inevitable in the long-term, even though at a reduced scale; by whom and where would logically involve a look at the underdeveloped countries.

It is becoming increasingly difficult to pigeon-hole Third World countries as an amorphous group. Whilst many share common problems of development, generalized statements would be both unfair and misleading. From the exploration and development point of view, countries such as Brazil, Chile, Indonesia, Malaysia, Morocco, Mexico, India, China, and even Papua New Guinea cannot be included in general discussion with such countries as Haiti, Guyana, Colombia, Sierra Leone, Tanzania, Guatemala, and Burma. This examination of the future of Third World countries in which exploration and development is more rudimentary because, regardless of potential, the level of work completed has been minimal (i.e. Kenya, Honduras, and so on), development up to the expected level has not occurred for a variety of reasons not directly related to mining potential (i.e. Bolivia, Zambia, and so on) because of declining grades and mineral prices with traditional deposits, increased production costs, foreign exchange and working capital shortages, limited investment, and labour problems. A declining industry in a declining economy has very little hope of salvage unless major changes occur. As mentioned previously, the 1980s have heralded a turning point in traditional industrial development and the mining industry overall must adjust if it wishes to survive as we know it.

EXPLORATION PATTERNS AND FINANCING

The International Private Sector

Over the short term, no fundamental changes are foreseen to present practices by the major international mining companies with respect to exploration and development in the Third World. With obvious exceptions, where for a variety of reasons, major companies have "traditional" committed programs in certain countries, a general pattern is a total foreign exploration budget of between \$15 and \$20 million, of which 90 percent is spent in the USA, Canada, and Australia, 5 percent in Europe and only 5 percent in the developing countries. This 5 percent, translated into about \$1 million is also quite specific in use in that it is directed at (a) very few countries, and (b) very specific targets. Except for few exceptions, the country lists are similar with few being targeted outside at groups that would include the Pacific, PNG, Indonesia, specific West African countries with Ghana now emerging attractively because of changed policies, Chile, Peru, and Brazil. As far as targets are concerned, gold is preeminent. Generally, these present and foreseen future patterns of exploration conform with the findings of Eggert (1984). This survey found that corporate exploration is similar to other forms of investment and responds to an interplay of economic, political, and technical factors influencing the expected revenues, costs, and risks. It is also obvious that the distribution of funds with respect to commodities and countries is closely tied to mineral prices and geological potential. In particular, new finds in an area tend immediately to generate investor response.

A simplified analysis of corporate policy with respect to the developing countries is quite straightforward; if the geology is right, the mineralization potential good, and Government policies perceived to be encouraging, then staged investment may be pursued, particularly for gold-based projects. This perfectly logical policy poses serious problems for many of the developing countries both now and in the future. It may be argued that many of these problems are self-imposed. On the other hand, many are caused by ignorance of the mining industry in general, conditions often beyond control of those delegated to implement mining programs and lack of confidence, good advice, and experienced personnel. Major identified problems which developing countries will continue to face in developing their mineral resource potential are as follows:

1. reduced exploration budgets directed at favored countries
2. limited enthusiasm for commodities outside gold, platinum, silver, special metals, and possibly zinc
3. minimum deposit size and cash flow requirements of nearly all major companies (i.e. reserves of 500 000 to 1 000 000 ounces of gold

or 50 000 ounces p.a. gold production or minimum cash flow of \$10 to \$15 million p.a.)

4. lack of acceptable development strategy, mining, and investment codes
5. lack of proven ability to work in good faith with the private sector
6. real political instability, chaos, warfare, severe security problems, and so on
7. perceived political instability; the unknown combined with historic problems
8. lack of confidence, experience, and capability to conclude agreements

Apart from the obvious and insurmountable technical problems — poor geology — it is thought, except in cases of major political turmoil, that many of these problems can eventually be overcome through a combined effort between the countries themselves, the private sector, and international institutions such as the United Nations, and the World Bank family, including IFC and IDA windows. In addition, the private sector itself is realizing that future profitability will need to be geared to scaled-down operations. The future must lie not just only in gold (including low-grade bulk tonnage targets), but also in high-grade tonnage mixed sulphides. Any move in this direction will certainly be a positive one for the developing countries.

Bilateral Assistance

The general thrust of this assistance, often lacking in co-ordination, is toward the basic gathering of geological information and upgrading of local facilities. Presently, most bilateral programs do not result directly in new mine finding or development. If such assistance can be harnessed by an international agency which is playing a lead role in mining sector development, then bilateral funding could contribute much more effectively than at present. All assistance must be strategy focused and co-ordinated.

The United Nations

The work of the United Nations in the minerals field, more specifically, the United Nations Department of Technical Cooperation for Development (UNDTCD), is presented in detail by J. Guy-Bray (this volume, Paper 65). This presentation will show that the ongoing technical assistance program, largely grant financed through the United Nations Development Program (UNDP), is at a level of \$15 to \$20 million per year. As virtually all projects contain a host-government financing component of the order of 50 percent of project costs, total expenditures are in the range of \$20 to \$30 million per year.

As nearly all projects contain training, institute strengthening, and equipment components, it is very difficult to identify how much money is actually invested directly into exploration and development work. A reasonable estimate would be between \$6

million and \$8 million annually. Unlike the 1960s and 1970s, when a large proportion of United Nations work was concentrated, with some success (Carman 1977), on large assistance in mine promotion and development and in improving government ability to manage private sector investment, project evaluation, financial analysis, development of legislation, and agreements. This is regarded as being a positive move. The gradual learning process and hands-on assistance made available to governments through this mechanism will help to alleviate some of the major problems identified above.

A more junior arm of the United Nations assistance to mineral development is through the United Nations Revolving Fund (UNRFNRE). Rather than direct grant assistance, this program is more focused on mine finding. There are no training and equipment components other than that required to get the job done. Also, unlike other UN work, all project costs, and therefore risks, are borne by the Fund. If discovered deposits are brought into production, there is a requirement for replenishment into the Fund equivalent to 2 percent of gross sales (1 percent for Least Developed Countries), otherwise expended funds are considered as grant assistance. The Fund may also work out, but through loan financing with conditions similar to the World Bank window. More details of the UN Revolving Fund have been discussed by Fozzard *et al.* (1984). There is considerable merit in the UN Revolving Fund approach in that no risks and no costs are incurred by governments unless a positive cash flow is developed. Eventual income from successful projects will be channelled back into exploration and development.

On the other hand, the UN Revolving Fund does have severe limitations; the greatest by far are financial. Unlike the UNDP (financing agency of regular UNDTCD assistance), which can generally count on a guaranteed yearly income from donors, financing to the Fund is limited with few major donors. Total donor and other income to the Fund since its creation in 1975 has been close to \$60 million, and by the end of 1986, close to \$50 million had been expended on projects in about 22 countries. Financial limitations not only restrict the scope of the program worldwide, but also the amount of funding on specific projects to bring a discovery to the point where it is attractive to investors. No income has yet been generated through replenishment payments. Two precious metal deposits found relatively early in the Fund's work, one in Ecuador and one in Argentina, could possibly have been close to development, but the respective governments found it difficult to generate investment enthusiasm. This reflects the second greatest difficulty being faced by the Fund; bridging the gap between discovery and follow-up. This often relates directly to such problems as absence of a development strategy, lack of

experience and ability in concluding agreements, unacceptable legislation, and fear of the unknown.

THE INTERNATIONAL BANK FOR RECONSTRUCTION AND DEVELOPMENT (IBRD)

The World Bank Group consists of two institutions, the World Bank and the International Finance Corporation (IFC), and three leading windows, the World Bank, the International Development Association (IDA), and IFC. The greatest sources of funding are provided through the World Bank window. In the fiscal year ending June 1987, approved loans totaled \$14.2 billion. Over the last 30 years, since 1957, the World Bank has been involved in more than 50 mining projects, the total value of which is close to \$9.0 billion, of which the Bank has provided some \$2.6 billion.

The IDA window provides soft loans with a 10-year grace period. Credits approved during the fiscal year 1987 totaled \$3.5 billion. The IFC's objective is to supply venture capital and to stimulate the local private sector and to promote the international flow of private capital to the developing countries. Unlike the World Bank, the IFC can make direct equity investments and can organize and lead loan syndications. Over the last 15 years, the IFC has lent or participated in equity of 68 mining projects to a total of about \$700 million. The size of loans in relation to total project costs are normally between 15 percent and 30 percent. A critical part of the technical preparation of a World Bank mining project is project management and monitoring. A strong, capable, and experienced management is considered an essential ingredient.

Bank-financed projects must be financially viable, and, it is the goal of both the World Bank and the IFC to mobilize as much outside capital as possible to help in the financing of its projects. Both the Bank and IFC will therefore, assist the project sponsor in securing outside financing from international and bilateral sources, commercial banks, and equipment suppliers. This is fundamentally important in bringing together the financial and technical strengths required by the developing countries in their mineral development efforts.

Under its technical assistance work, the Bank finances exploration, feasibility, and engineering studies as well as assistance to the total mineral sector. Objectives are not only to upgrade specific projects but also to increase the country's ability to negotiate realistic agreements with foreign investors. Included in such technical assistance projects are overall assessments of a country's mineral potential and determining the most appropriate route to development or re-orientation.

It is the objective of the World Bank to assist the development of the mining industry in the developing countries in a manner which is economically and

technically sound. This assistance in many instances is in the role of a lead advisor or honest broker, a role which is welcomed by both private industry and government alike. A detailed updated overview of the role of the World Bank in the international minerals industry has just been presented by Kotschwar (1987) at the Mining Conference in Leoben.

A NEW MECHANISM FOR DEVELOPMENT

The potential financing available through IBRD combined particularly with its broad ability to assist throughout the sector at every level of development from exploration through to production, could make it a mechanism for generating and securing high risk investment in the developing countries. It could provide the essential early bond between foreign and local investors and host governments. In so doing, the gap between exploration and development would be successfully bridged.

As an added incentive to investment in the developing countries, the World Bank is sponsoring the creation of the Multilateral Investment Guarantee Agency (MIGA). This agency is designed to stimulate capital flows to its member countries by according foreign investors guarantee protection against non-commercial risks, by providing technical and advisory services to member governments and by facilitating policy co-operation among its member governments to improve and stabilize investment climates. Similar to national investment guarantee programs, MIGA will cover 70 to 90 percent of the investment. The following risks will be covered:

1. restrictions on currency conversion and transfer
2. loss from legislative actions; deprivation of ownership, control, and benefits
3. repudiation of contracts
4. armed conflict or civil unrest
5. other non-commercial risks on a case by case basis

The convention will enter into force upon ratification by five capital exporting countries. To date, the convention has been signed by 12 developed countries and 46 developing countries and has been ratified by 20. MIGA is expected to come into being in late 1987 or early 1988. The capital base is Special Drawing Rights \$1 billion (fixed at the equivalent of \$1.088 billion).

In addition, the World Bank through IFC is about to launch the GRIP program (Guaranteed Recovery of Investment Principal). Under GRIP, an investor, instead of investing funds in his own name, could deposit them with IFC which would then use these funds for equity subscription into a specific venture. Returns on equity would be shared in an agreed ratio between IFC and the investor. At the end of an agreed period, e.g. 10 years, the investor could either cash in his deposit at the nominal

amount, purchase the shares from IFC at market value, or extend.

In a way, the MIGA and IFC schemes are complementary and mutually supportive but obviously, with respect to mining projects, relate more to mine development. Whereas these schemes should have a positive effect on upstream exploration activities in the developing countries by creating visible downstream stability, they will not directly forge the links between governments and investors early enough in the cycle; exploration through to feasibility. To provide "honest brokerage" throughout the cycle by means of a tripartite agreement between an organization such as the World Bank, private industry, and governments, could provide the right stimulus to allow more vigorous pursuit and development of the developing countries mineral resources.

A POTENTIAL INTERNATIONAL JOINT-VENTURE AGREEMENT

When exploration potential is recognized from previous work by the government itself, or through private, bilateral, or international programs, contact can be established between interested parties with a view to exploration and development under what could be termed an international joint-venture exploration program (INJOVEP).

If not in place already, the first requirement would be the establishment of a mining regime which would be equitable to both major parties involved; the government and the investors. A recent development which is finding acceptance in developing countries is the concept of a model investment agreement which covers the total mining, fiscal, and investment regime of a particular project or projects. (T. Walde, United Nations Department of Technical Cooperation, New York, personal communication, 1986 and 1987). It is not feasible to consider a boilerplate model as has been suggested, (I. Newport, World Bank, personal communication, 1987), for considerable tailoring will be required depending on the project and the host country. Of particular importance to the investors would be an equitable taxation regime, reasonable equity participation, management control, repatriation of profits, tax incentives through reinvestment, depreciation, waivers, or reduced import levies. Of fairness to both parties would be a taxation regime geared to project rate of return. Of importance to governments should be sound management to maximize profitability and hence their income, close involvement (not interference) in all aspects of project development, social and infrastructural development, transfer of technology, and equity participation.

It is obviously important that game rules for future development are clearly spelled out in an INJOVEP agreement. Both the United Nations and the World Bank have been involved over a long time in assisting governments in all aspects of mining and associated fiscal legislation and codes as well as pro-

ject financial analysis. International assistance could therefore be made available on first recognition of a potential exploration joint-venture.

For the exploration venture itself, a parallel specific project investor agreement, or at least basic criteria, would need to be developed based on third-party assessment of project viability, design, technical, and financial requirements. In most circumstances, a phased approach would be essential.

In cases where an interested investor has not been identified or where the government and the international agency considered there was a need to identify a list of potential clients, a promotional brochure would be issued setting out the technical details, the basics of the mining and fiscal regimes, governing clauses, and project design and profile. The inclusion of MIGA and/or GRIP type options with respect to future development should provide a further stabilizing influence on the project as could reference to the World Bank's International Centre for the Settlement of Investment Disputes (ICSID).

It is generally found to be more stabilizing, and beneficial to a foreign investor, if a national company can become involved in the project. The aim, therefore, would be to develop a joint-venture with a mixed foreign/national enterprise, the government (where the national enterprise is not a public entity) with possible World Bank signature guarantees and/or IFC equity participation. International guarantees could probably be covered by existing loan and guarantee agreements presently used by IBRD. Investment ratios would vary on a case by case basis ranging from full private financing for any viable grassroots program that may be identified to a potential 51 percent government, 49 percent private participation. Partial financing of government participation could be obtained from the international participants if required. If the project did not reach feasibility stage, then withdrawal options would be required. Guarantees against early withdrawal by the private investor would be required through minimum commitments.

At the feasibility stage, the INJOVEP Agreement would provide options for full equity participation as well as guaranteed capital commitments including direct participation of the international partner similar to that being offered by IFC through the GRIP program.

It is considered that such a mechanism would provide numerous advantages:

1. Investment of an international organization would ameliorate real or perceived confrontations between the private sector and the host country and would thus provide numerous political advantages. The International participant would ensure fair play on both teams.

2. The government would benefit from third-party assessment and support which would provide confidence in project viability.
3. Through the legal enforcement of such a joint-venture agreement, a chance would be provided to develop a bond of mutual confidence between foreign investors and the host country; an essential requirement for further investment and development.
4. For the private investor, risk and finance sharing should enhance project attractiveness.
5. The private investor would also find comfort in knowing that the international participant is also providing a watchdog role. A great deal of stability would thus be provided to their investment.

A bad experience, either by a host country or a foreign investor, can detract from mining investment for decades. A good and successful experience can rapidly generate a snowball effect. These facts are well known to industry, but are often not readily appreciated by many of the developing countries.

CONCLUSION

A major change is occurring within the mining industry worldwide, and the general trend of lower consumption of prime raw materials will be irreversible. The "good old days" may be replaced by the "good new days" but this will require scaling down of operations and considerable product flexibility.

Gold fever cannot last forever and because of the financial and consumptions limitations and despite the exceedingly depressed scenario, smaller higher grade deposits will need to be brought into production; the scaling down process. Many of these deposits occur in the developing countries as do specialty metals and materials for which there will be an increasing demand, but, again, at much smaller scales than the billion dollar projects of the past.

For developing countries, the export of mining products is often one of the few routes to foreign exchange. The technical experience and financial wisdom of the private mining sector are desperately required to bring developing country deposits into economic production.

The impediments and obstacles to foreign mining investment in real or perceived high risk environments are well known. More often than not these impediments are spawned from mistrust and ignorance. An effort must be made on both sides, assisted by the international community, if this deadlock is to be broken.

International organizations, the United Nations and the World Bank, are committed to mining development programs. The World Bank in particular has the financial, technical, and administrative capacity to play a direct arbitral dispute facility (ICSID), the new multilateral investment guarantee agency (MIGA), and IFC's equity participation

through GRIP. It is in a good position to offer the required stimulus and stability for mine development projects in the Third World.

Many potential mining projects fail because of lack of involvement of a competent sponsor at the early, upstream, exploration phase. A new mechanism such as an international joint-venture exploration program (INJOVEP) might bridge the gap and force a bond of stability between private investors and often insecure, skeptical, and inexperienced governments. This is obviously not the only solution but it would provide a vehicle of stability, fair play, and vital reduction of risk.

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3. Uses (and Abuses) of Ore Deposit Models in Mineral Exploration

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ABSTRACT

An ore deposit model is a conceptual and/or empirical standard, embodying both the descriptive features of the deposit type, and an explanation of these features in terms of geological processes. The descriptive features of models serve as criteria for exploration area selection ("area selection criteria"). How they are used in this function depends on the scale of their spatial association with ore, on our confidence that they are reliable indicators of ore, and on the extent to which they are preferentially associated with economically better deposits. The geological, geochemical, and geophysical techniques used in exploration, and exploration strategy depend on area selection criteria. The relative importance of area selection criteria can be determined from their relative frequency of association with ore in a representative sample of the deposit population, resulting in an empirical model. A genetic model is derived by considering the genetic relationship of area selection criteria to ore. The weak links in model building are the lack of effort which goes into systematically assembling the data on the known population of deposits, and the weak scientific underpinnings of the genetic interpretation. Both of these factors influence exploration by leading to inappropriate assessments of the relative importance of area selection criteria. In addition, there are a number of human foibles which commonly lead to shortcomings in the development and use of models. The most significant of these is our tendency to rely too much on too simple models. We do this to avoid the discomfort of uncertainty and confusion which inevitably comes when we are called on to assess exploration situations.

The history of exploration for massive base-metal sulphide deposits and gold deposits in the Canadian Shield provide a good illustration of the influence of models on area selection criteria, and thereby, on exploration strategy and techniques.

INTRODUCTION

A model in geology is a conceptual and/or empirical standard which embodies the essential features of some population of natural geological phenomena. Although a model can be strictly descriptive, most contain interpretive elements that explain the relationships among the various descriptive features in terms of geological processes. Models of ore deposits

are widely used in mineral exploration as a basis for predicting the exploration potential of areas which may range in scale from large regions down to individual ore zones. Everyone uses models, but often little thought is given to how models are built, how they influence exploration programs, and how they can be improved.

The objective of this paper is to examine the structure of ore deposit models and their role in the mineral exploration process. In his famous book, "The Structure of Scientific Revolutions", Kuhn (1962) argued that models are used, consciously or not, to predict in virtually all of our everyday interactions with our environment, including in scientific research. If this view is accepted, then models should represent as close an approximation as possible to reality, if they are to properly guide us. However, it should be emphasized that models are a two-edged sword. On the one hand, they are a powerful means of organizing data in a form that enhances understanding and prediction. But on the other hand, by operating to exclude perception of data which does not fit the model, they have a soporific effect, that may lead to unjustified confidence in the application of the model. These concepts are illustrated by describing the influence on exploration strategy and techniques of historical changes in models for base-metal, volcanogenic massive sulphide, and for gold deposits.

MINERAL EXPLORATION

Mineral exploration involves the progressive reduction in the size of the area being explored until a mine is found (Figure 3.1). The starting point may be a region the size of a continent, or simply one level in a mine. Whatever its size, the objective of exploration is to focus attention progressively on the most favourable parts of the area so that as exploration proceeds, the chances of an economic mineral deposit being found continuously increase. Area reduction normally takes place in steps which are separated by area selection "decision points" (Figure 3.2). For example, in a regional reconnaissance program, the first decision point might follow the completion of large-scale geochemical and geophysical surveys, at which time a number of claim groups might be staked or optioned.

Area selection in mineral exploration is based on the presence or absence of specific geological features, or alternatively, geophysical and geochemical features which reflect geological features. These

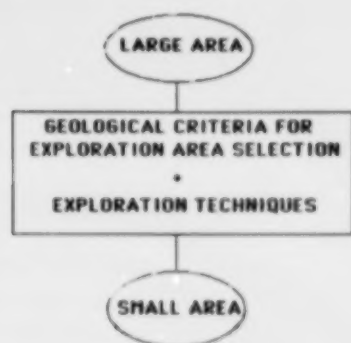


Figure 3.1. The exploration process: exploration techniques (geological, geophysical, and geochemical) are used to measure the distribution of area selection criteria so that the most prospective parts of a large exploration area can be selected for further exploration.

features can be termed "criteria for exploration area selection" or simply, "area selection criteria" (see Figure 3.1). Area selection criteria are concrete, measurable features, not concepts. For example, it might be considered that volcanic centres are an important regional-scale area selection criterion for volcanogenic massive sulphide deposits. However, "volcanic centre" is not a feature which shows on the legend of most geological maps. Rather, it is an interpretation based on the distribution and configuration of specific lithologies and structures in an area. The map patterns which indicate "volcanic centre" are the concrete reality, and it is these map patterns that comprise the area selection criteria.

Much of the work of exploration consists of defining the distribution of area selection criteria in the exploration area. The term "exploration strategy" can be used to refer to the sequence of activities

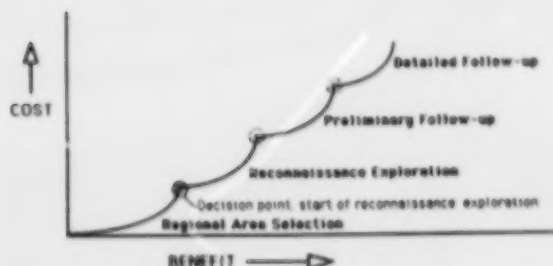


Figure 3.2. Diagrammatic representation of the exploration sequence, in terms of cost/benefit ratio. The optimal exploration strategy is that succession of exploration activities which in aggregate has the lowest total cost, relative to the economic return. Each type of exploration activity gives a diminishing return on investment as it is pursued, and is replaced by the next most cost-efficient type of activity at the decision points where the size of the area being explored is reduced.

which results in the progressive reduction in the size of the exploration area. The best exploration strategy optimizes the balance between cost and effectiveness in the area selection process (see Figure 3.2). Two factors are critical to good exploration strategy:

1. optimizing on the cost, in relation to the effectiveness, of methods used to determine the presence or absence of features on which the area selection process is based
2. using the appropriate criteria for exploration area selection, and correctly assessing the relative importance of these

Most of the papers being given at this conference are concerned with the first factor. It is the second aspect of exploration strategy that is the main concern of this paper.

MODELS AS SYSTEMS WHICH "RATE" AREA SELECTION CRITERIA

Area selection criteria must not only be features which are spatially associated with ore, but they must also be genetically related to ore in some way. Without this genetic link, the spatial association would be fortuitous or accidental, and therefore not a reliable guide to ore. In addition, area selection criteria, to be useful, must be relatively easily identified, normally by field techniques. For example, the type of gold deposit which occurs in greenstone belts is commonly associated with certain types of felsic hypabyssal intrusions, and therefore the presence of these intrusions is a useful area selection criterion, readily applied in a field situation (Hodgson *et al.* 1982). In contrast, the observation that fluid inclusions in Archean gold deposits are CO₂-rich, while genetically significant (Wood *et al.* 1986), is not, at our present level of geological understanding, a criterion that can be practically applied in the area selection process in most instances. In the case of epithermal-type gold deposits, on the other hand, the gas content of fluid inclusions is a criterion for area selection (Norman *et al.* 1988).

Area selection criteria can be ordered in a three-dimensional hierarchy, according to:

1. the scale at which they are associated with mineralization, and thus the scale of area selection for which they are used
2. the confidence one has that a feature is an essential (not fortuitous) part of the ore environment
3. their relation (if any) to the economic quality of a deposit

Area selection criteria are scale-specific: what is important at one scale may be irrelevant at another. For example, there is an association of Archean gold mining camps with the contacts of mafic $\pm$ ultramafic volcanic sequences with sedimentary rock sequences, but this feature is of little or no use in

selecting drill targets within mining camps (Figure 3.3). Large-scale area selection criteria are more important than small-scale criteria, since even the most technically strong program cannot succeed if it is carried out in the wrong general area. However, the scale at which an area selection criterion is applicable, and the confidence that one has that the feature is related to ore, tend to be inversely related — it generally is more difficult to characterize, and determine the genetic relations among large-scale phenomena than it is among small-scale phenomena. The larger-scale area selection criteria are commonly considered to define the geological environment which is favourable for mineralization, whereas the smaller-scale features define the deposit (Figure 3.4).

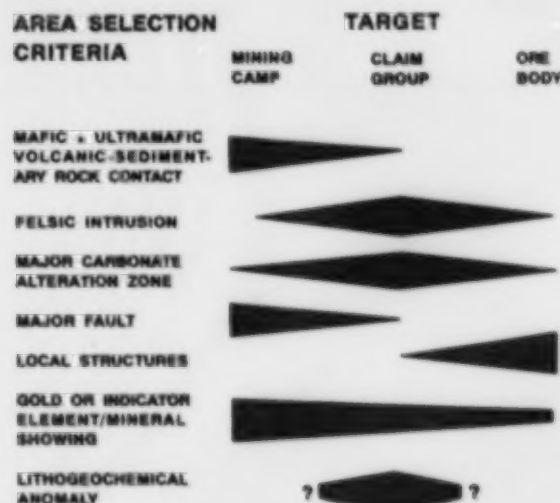


Figure 3.3. Area selection criteria for gold deposits in the Superior Province of the Canadian Shield, showing how the relative importance of different criteria changes as target size decreases during the exploration process (from Hodgson et al. 1982).

VOLCANOGENIC MASSIVE SULPHIDE DEPOSITS



Figure 3.4. Diagrammatic illustration showing how the distinction between geological characteristics of the "deposit", and the geological characteristics of the "deposit environment" depends on the scale of the geological feature associated with mineralization.

One of the major problems in exploration is assessing the reliability of criteria for area selection, the second dimension of the rating hierarchy above. There are basically two approaches to this problem. In the first approach, the distribution of features in the known natural population of deposits is recorded. Features are rated for their reliability according to their relative frequency of association with ore, and their absence in areas without ore. Thus, a feature which occurs in nine out of ten deposits, but is otherwise rare would be considered a much more significant area selection criterion than a feature which occurs in only half the deposits, and also occurs in areas without mineralization. A model generated in this manner is termed an "empirical model". To construct an empirical model, the presence or absence of each feature must be recorded for a statistically significant and unbiased sample of the entire population. Herein lies the main weakness of the purely empirical approach: data for only a small part of the population cannot be used to formulate the model. For example, fluid inclusion or isotope data on a single deposit cannot be used as empirical area selection criteria, because without applying interpretive, genetic arguments, it is not possible to say that the data will be characteristic of other deposits of the total population. However, these data may be critical to understanding the origin of ore-forming fluids, which in turn may be critical to assessing the importance and reliability of certain lithological associations as exploration guides. Another major weakness of empirical models is they cannot predict features not in the original data base.

The second type of approach to rating area selection criteria is through the use of a genetic model. Genetic models differ from empirical models in that they explain empirical relationships in terms of the causative geological processes. The descriptive features are then rated in importance and reliability as area selection criteria, according to their relationship to the ore-forming process. For example, if it was thought that ore solutions were derived from the same magma as gave rise to felsic intrusions associated with a deposit, the petrological character of the intrusions would be worthy of detailed study in the hope that diagnostic characteristics might be identified which would serve as area selection criteria. But if the association of mineralization and felsic intrusion was considered only the result of their being in the same structural system, then the presence and type of intrusion would seem less important. Genetic models are capable of predicting relationships and data not in the original data base, but have the weakness of typically being based predominantly on a few well studied deposits (which may not be typical). They also tend to ignore or debase features not "explained" by the geological theories in vogue at the time. Invariably it is beneficial to use the theory and data of geology to upgrade a raw empirical model to a more refined genetic model, provided

that features which show a strong association with ore, but cannot be explained, are retained as area selection criteria.

A little-considered aspect of mineral deposits geology is the relation between geological features and economic quality of deposits. Many explorationists believe that the economically better deposits of any one type are more mineralogically, structurally, and petrologically complex than the economically poorer deposits of the same type. Hodgson and Troop (in press) noted an empirical relationship between the presence of the certain minerals, including scheelite, tourmaline, molybdenite, sphalerite, and galena, and the economic quality of gold deposits in the Abitibi Belt in Ontario. However, there are few quantitative studies of such phenomena, and few geological studies of any kind of economically poor deposits.

THE IDEAL METHOD OF MODEL BUILDING

The ideal method of model building, and the generation of a set of area selection criteria is outlined in Figure 3.5. Compilation of data on the known population of deposits is an essential first stage in model building. This process can be expected to result in many surprises, since the tendency is to generalize to the world-scale the essence of parochial individual experience. Using models with an incomplete descriptive base is a common cause of poor exploration decisions. For example, failure to recognize that not all large porphyry copper deposits of the world have well-developed quartz-sericite-pyrite alteration envelopes led a generation of geologists from large, southwest USA-based copper mining companies to write off the low-pyrite deposits of the Highland Valley, B.C., as economically unimportant (Mustard 1976). Lack of awareness of the

common association of molybdenite with gold, well documented in the descriptive literature on Ontario gold deposits, and the idea that large gold deposits do not occur in high metamorphic grade rocks (contradicted by many examples, including the super-giant Kolar deposit of India) were among the factors which led numerous geologists to underestimate the potential of the Hemlo deposit.

Detailed studies of typical deposits, especially if these are representative of the range of characteristics found in the population as a whole, are invaluable in defining in detail the spatial, temporal, and genetic relationships among deposit characteristics. For example, although the compilation of Lowell and Guilbert (1970) was invaluable in defining the general descriptive characteristics of porphyry copper deposits (albeit biased towards southwest USA deposits), it was not until the detailed study of Gustafson and Hunt (1976) of El Salvador that the relationships among many of these features was determined, and their genetic meaning correctly interpreted.

Following compilation and during the progress of detailed studies of typical deposits, the significance of features is analyzed in terms of known geological processes and physical-chemical theory. This leads to the formulation of an ore-forming process model, in the light of which, the genetic significance of the features is assessed and their reliability as area selection criteria is rated. This assessment must be done on a continuing basis, since the theory and data base of geology are evolving rapidly. Correctly interpreting descriptive data presents a special problem for industry geologists, who have little time to keep current with the flood of new geological literature, and even less time to upgrade educational skills so they are able to assess the value of this material.

Rationalizing the descriptive features of a population of deposits in terms of the ore-forming process commonly results in questions being raised about the validity of the original data base. The appropriate action at this point is to check out the facts by re-examining the field relations. However, in many cases this is not done, but instead the offending facts are rejected as "unreasonable" (i.e. errors in measurement), or "unimportant anomalies". The formulator of the model is normally uncomfortable with this and other expediciencies involved in the model-building process, and will apply the model cautiously, in full awareness of its imperfections. Typically not so cautious are the second generation of users, who see the model as reality, not an imperfect abstraction of reality, and who may actively avoid or reject any fact which does not fit this reality. Personal contact between the formulators of models (mostly academic and government geologists) and explorationists can be very useful in increasing awareness of the limitations of models.

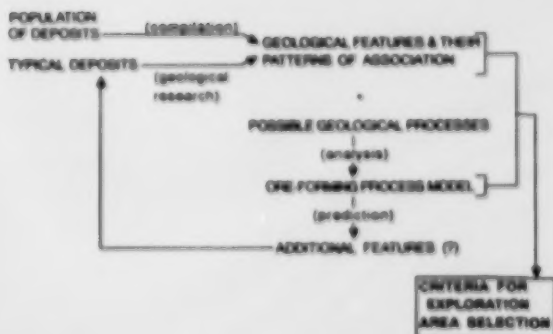


Figure 3.5. Idealized method for building a genetic model for an ore deposit type, and using it to rate area selection criteria.

PITFALLS IN THE MAKING AND USING OF MODELS

A number of human foibles interfere with the ideal process of model building, and the proper use of models in exploration. These attitudes commonly take the form of "corporate or institutional cults", and pervade industry, and academic and government institutions to an equal extent. Human foibles are most insidious and deceptive when people are organized in groups, since individuals tend to lose the restraining effects of their conscience when they are in groups. Furthermore, self-interest dictates that an individual intent on promotion or recognition within a group will not jeopardize his aspirations by contradicting what he perceives to be the accepted dogma of the group. Each of these "cults" incorporates attitudes that are valid: the error comes in the narrowness of the vision, and in the quasi-religious zeal with which one path is followed, to the exclusion of all others.

One of the most common of these cults is the "fads and fashions" school (Figure 3.6). The defining characteristic here is an obsession with being up-to-date and in possession of the latest, most modern model. An infatuation with the new, the improved, is a characteristic of our whole society, and is exploited by all who are in the business of selling, whether it be soap, geophysical instruments, scientific concepts, or mineral deposit models. Implicit in this cult is a sort of blind faith in the inevitability of progress, the idea that if it is new, then it must be improved. True believers in progress on the consumer end of geology, the explorationists, are symbiotically linked to like-minded academics and other researchers who feel that unless their work results in new models (and the newer, the better), they

are not successful. The policies of scientific funding agencies reflect, and at the same time promote this attitude, exerting a constant pressure on researchers to come up with extravagant and radical models which differ as much as possible from those previously proposed to explain the same phenomena, in order to justify increasing expenditures on complex modern equipment. An allied phenomenon, almost as religious in character, is the attitude that if the data and arguments upon which the model is based are not obscure and incomprehensible, then the model cannot really be new, and therefore, cannot really be valid.

The proliferation of "trendy" models is also a consequence of the increasing specialization in science, combined with the emphasis on "productivity" of researchers, i.e. the number of publications generated per research dollar spent. This has resulted in fragmentation of the literature into numerous small contributions, commonly reporting data collected without consideration of phenomena outside of the area of specialization. Models based on this data may quite adequately explain it, but may be strongly at odds with other data on the deposit.

Related to the fads and fashions school is the "cult of the panacea" (Figure 3.7). This is the attitude (perhaps better termed a faith) that out there, somewhere, is the ultimate area selection criterion that will banish forever all the hard work of mineral exploration. After its discovery, all other data will be irrelevant, all arguments and controversy silenced, forever. This ultimate criterion will only be detectable with the newest and most expensive equipment, and why or how it works will be totally incomprehensible to all but a few high priests of science. The search for a panacea to the problems of area selection in exploration is laudable, and has resulted in

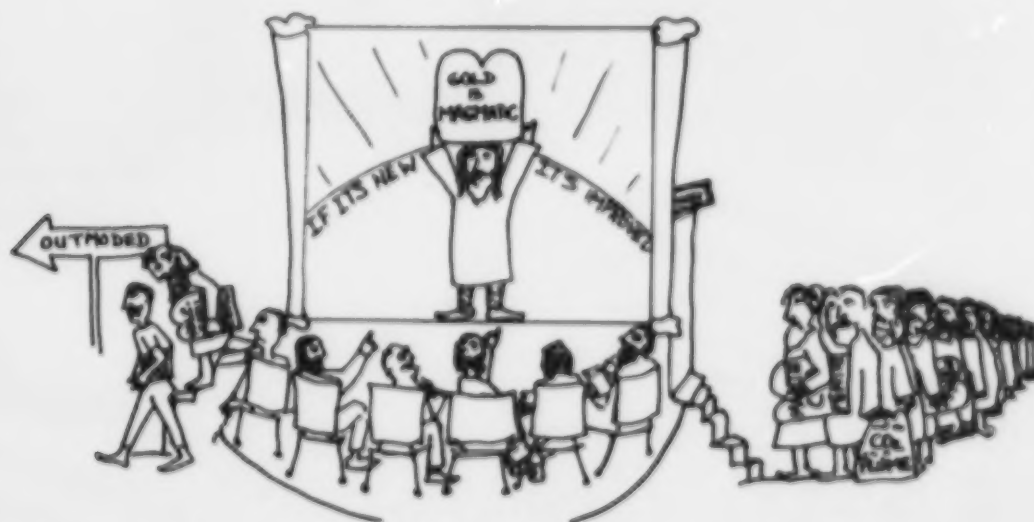


Figure 3.6. Pitfalls in the making and using of models: the school of fads and fashions.

many significant advances; the problem comes with really believing that there is such a thing, and with the readiness of some exploration geologists to throw all traditional evidence (and plain common sense) to the wind when they are presented with yet one more data type purported to provide the final answer.

In complete contrast to the fads and fashions cult is the "cult of romantics" who reject out-of-hand all that is new because it has been generated in the decadent hothouses of modern universities or government (Figure 3.8). Cult members commonly have an antipathy for models of any type, because the recognition that models play a role in exploration is, in itself, viewed as "bookish" and therefore, suspect. Most romantics believe that the practice of science and exploration is a completely objective process, which is unnecessarily biased by subjective constructs like models. They are constantly reaffirmed in their faith by the actions of those who fail through the use of inadequate models, or the misuse of good models, and by the inevitable occasional failures of modern technology. Every discovery by someone who has consciously swum against the current of popular models, every failure by a modern,

technology-oriented multinational corporation is heralded as a justification of their point of view.

Another common cult is that of the "corporate iconoclasts", who have their own models, carefully nurtured and protected from outside influences (Figure 3.9). Corporate iconoclasm seems to be a form of nationalism, arising, like nationalism, from our need to feel that we are an integral and important part of a group, not an isolated and alienated cog in some vast and incomprehensible machine. The models developed and used in such groups may in fact be superior, but the chances of them remaining so, in such a protected and often secretive environment, are poor. In this environment, for any changes to be acceptable, they must be invented within the group, since by definition the group is superior to the outside world. This type of arrogance, while perhaps conducive to the development of group solidarity, tends to generate a need to prove that the corporate or institutional model is superior and valid, which can lead to selective perception, i.e. only that data which supports the model is seen, and the rest is ignored.

In many organizations there is a policy of promoting specialization, in the interest of efficiency. The idea is that each does his special job, which he then gets extremely good at doing. This is the cult of "role specialization" (Figure 3.10). A problem arises here because the role of data gathering (field work), and data interpretation (office work) become uncoupled, with the inevitable outcome that nothing that is not specifically asked for by the data interpreters ever finds its way into the data base. Models in this environment have a very constraining influence, and are never subjected to the type of con-

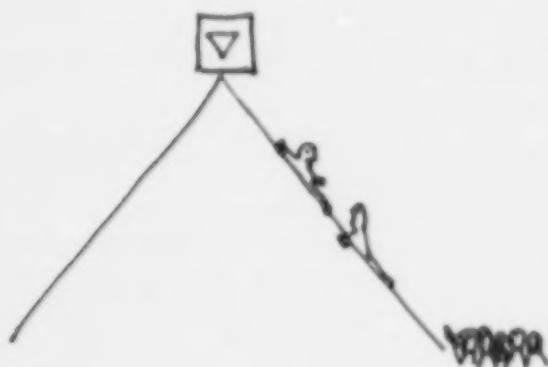


Figure 3.7. Pitfalls in the making and use of models: the cult of the panacea.



Figure 3.8. Pitfalls in the making and use of models: the cult of the romantics.

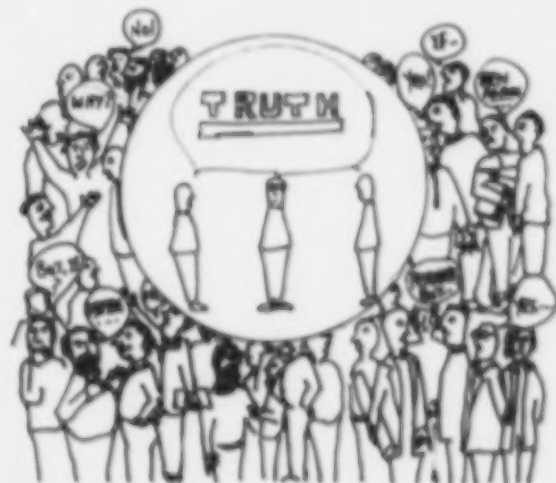


Figure 3.9. Pitfalls in the making and use of models: the corporate iconoclasts.

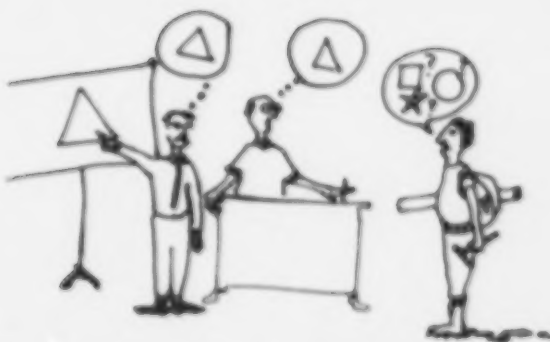


Figure 3.10. Pitfalls in the making and use of models: the school of rote specialization.

tinuous field testing needed to ensure that they are of optimal quality.

In summary, models are blamed for many mistakes, as well as being credited for many successes, in mineral exploration. But it is not the use of models which is the problem, since models are always used, whether this is admitted or not. Rather, the problem is which models are used (which involves how the models were constructed, and how they are kept up to date), and how they are used, (which involves the function of models in exploration).

The ultimate, ideal model incorporates all of the data on a known population of deposits, and explains these features in terms of an ore-forming process which is consistent with the rest of the data and theory of geology. Many ore deposit models fall short of this ideal by being based on too small a sample of the population, i.e. they have too parochial a bias. In addition, the scientific underpinning of many models are weak, because the full range of modern geological theory has not been considered in explaining the features of deposits in terms of the ore-forming process. Or the theory behind the model may have been adequate when the model was formulated, but advances in geology have since rendered it obsolete. A poor theoretical basis leads to incorrect assessments of the significance of the descriptive features of the model, and thus their relative importance as criteria for exploration area selection.

In application, most problems arise because of unwarranted veneration of specific models. This leads to models, with their necessarily condensed and idealized version of reality, becoming a comfortable substitute for reality, a crutch which allows the true believer to avoid the confusion and ambiguity of reality. A model, like any other concept in geology or science, is a tentative and necessarily imperfect creation which should be constantly tested as new field data and theoretical concepts become available. Models are guides to help sort the more important from the less important, and throw into bold

light the anomalies which do not fit. A model is developed and improved by being modified and elaborated to incorporate increasingly more of the unexplained data. It should never become a filter which allows only certain data to be seen.

It is unlikely that there will be an abrupt improvement in the published data base of mineral deposits geology, or in the proliferation of narrowly based and ill-considered models in the geological literature. Therefore, the onus is on the mineral explorationist to develop the attitudes and educational skills needed to assess the practical implications of new data and ideas. Education and experience provide the only real protection against scientific salesmanship.

MODELS IN CANADIAN MINERAL EXPLORATION

The history of mineral exploration in Canada has been dominated by the search for gold deposits, volcanogenic massive sulphide deposits, and porphyry copper deposits. Models for the first two types of deposits have changed radically in the years since modern geophysical and geochemical prospecting techniques have come into widespread use, and so they provide an excellent opportunity to examine the effect of models on exploration.

MODELS FOR VOLCANOGENIC MASSIVE SULPHIDE DEPOSITS

The first major volcanogenic massive sulphide (VMS) deposits discovered in eastern Canada, apart from those in Newfoundland (not part of Canada at the time) were the Horne, Waite, and Amulet deposits of the Noranda area, and the Normetal deposit located to the north of Noranda, discovered by prospectors in the early- to mid-1920s. Up until the early-1950s, these were interpreted as belonging to the general class of structurally controlled, epigenetic base-metal replacement deposits. In the mid- to late-1950s, there was a gradual evolution in thinking which finally cumulated in the presently accepted, exhalative-sedimentary model gaining ascendancy by the mid-1960s (see review by Lydon in Franklin *et al.* 1981, p.569-573). By the late-1960s this new model dominated the thinking of explorationists in eastern Canada.

The change in ideas about the origin of VMS deposits did not result in major changes in deposit-scale area selection criteria, since most of the important descriptive features of the deposits had been clearly recognized by earlier workers. However, the new ideas had a profound effect on the relative emphasis placed on these criteria. They also led to an entirely new definition of what constituted a favourable, larger-scale environment for ore occurrence, i.e. on the regional-scale criteria for exploration area selection. These relationships are outlined in Table 3.1 and Figure 3.11, and described below.

TABLE 3.1. AREA SELECTION CRITERIA FOR VOLCANOGENIC MASSIVE SULPHIDE DEPOSITS AND THEIR GENETIC SIGNIFICANCE ACCORDING TO THE LATE EPIGENETIC REPLACEMENT MODEL AND THE SYNVOLCANIC EXHALATIVE MODEL FOR ORE FORMATION.

FEATURE	GENETIC SIGNIFICANCE OF FEATURE	
	LATE EPIGENETIC REPLACEMENT	SYNVOLCANIC EXHALATIVE
ROCKS		
Felsic intrusive complex	Source of ore-forming fluids	Source of heat and possibly magmatic fluid components
Felsic volcanic, especially high-silica rhyolite domes, tuff-breccia complexes (near contact with)	Fluids trapped in permeable and reactive rhyolite below impermeable, unreactive basalt; competency contrast during deformation	Vent-proximal extrusions, hydrothermal explosion products formed during ore-favourable stage in evolution of volcanic complex
Mafic volcanic		
Lithic volcanoclastic layer, especially with sulphidic and/or altered clasts	Permeable and chemically reactive zones favourable for replacement	Hydrothermal explosion products, indicating submarine hot spring vent nearby
Sulphidic sediment layer	Zone of selective replacement; indicator of favourable horizon for ore occurrence	Distal exhalite; indicator of favourable horizon for ore occurrence
Abundant dikes	Fluid barriers confining ore solutions to rhyolite	Structure permeable to magma and ore fluids
STRUCTURES		
Faults, fractures	Magma and fluid conduits	Magma and fluid conduits
MINERALIZATION AND ALTERATION		
Chloritic pipe	Ore-related hydrothermal activity	Sub-sea floor, ore-related hydrothermal activity
Zn-, Fe addition; Na-depletion anomalies in footwall sequence	Ore-related hydrothermal activity	Widespread self-sealing of cap rock
Disseminated to massive sulphide	Partial to complete replacement of rhyolite	Sub-sea floor replacement grading to sea floor exhalite

The generalizations which follow are based on the description of the epigenetic model, as it was applied to the Noranda area, by Wilson (1941) and articles by Brown, Hawley, Price, Price and Bancroft, Sufel, and Scott in the first volume of "Structural Geology of Canadian Ore Deposits" (Canadian Institute of Mining and Metallurgy 1948). There are many reviews of the synvolcanic model, but that of Franklin *et al.* 1981 is as complete as any. Hodgson and Lydon (1977) described the implications of the synvolcanic model for exploration.

Epigenetic Replacement Model

According to the epigenetic replacement hypothesis, the major characteristics of VMS deposits, and the control of the localization of mineralization, could be explained in terms of four basic principles:

1. permeability variations in the host rocks, a function of both the original volcanic structures, and of later deformation
2. variations in the susceptibility of different rock types to alteration and replacement by reaction with hydrothermal solutions
3. the damming or constraining of fluid flow by impermeable and unreactive rock units, suitably positioned in relation to the favourable ore host rocks
4. the major, structurally controlled, fluid conduit or "plumbing" system

One of the key descriptive features of the deposits emphasized in early exploration was the association of mineralization with rhyolite, especially rhyolite breccias. The breccias were recognized as being mainly of volcanic origin, but some were considered to be of tectonic origin. Their favourability

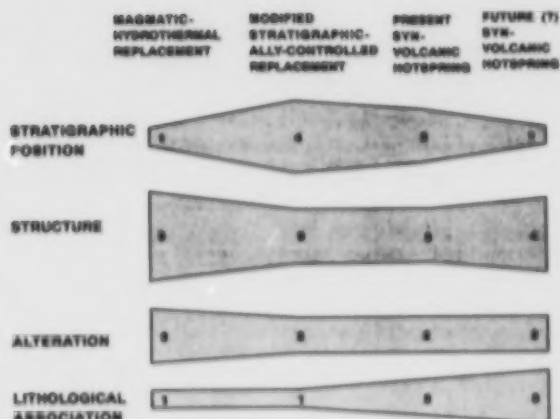


Figure 3.11. Diagrammatic representation of the change in relative emphasis on different area selection criteria with historical changes in the genetic model for volcanogenic massive sulphide deposits.

as host rocks derived from their permeability, and the susceptibility of rhyolite to replacement. The sharp contact between breccia-hosted ores and unmineralized "andesitic" (basaltic) flows, or dikes and irregular bodies of virtually unmineralized "diomite" (gabbro), was considered the result of the impermeability and unreactivity of mafic rocks. The mafic rocks were thought to have behaved as aquacludes, constraining fluid flow to the mineralized rhyolites. A domical shape was noted in the unmineralized basalt-mineralized rhyolite contact in several deposits: this was interpreted as due to cross folding. The occurrence of ore concentrations in such "fold hinges" was considered due to damming and ponding of ore-forming fluids.

It was also recognized that mineralization occurs within zones of Mg-Fe enriched and Na-Ca depleted altered rock, being most closely associated with chloritic alteration. Vertical, pipe-like alteration zones in the Waite-Amulet area were interpreted as hydrothermal fluid conduits tapping a magmatic fluid source at depth. The mineralized zones were thought to have formed where fluids were able to penetrate laterally from these conduits along permeable and chemically favourable rhyolite horizons. The importance of the Amulet Rhyolite-Amulet Andesite contact in the central Noranda area as a major site for mineralization was recognized, but was not emphasized in exploration as much as it would be after the synvolcanic model became accepted. Any similar contact intersected by the subvertical conduit system was thought to be equally prospective for ore.

Major emphasis was placed on fault and fracture systems as fluid conduits. In the Horne Mine in particular, faulting and shearing were considered the main reason why the deposit is localized in the

wedge-shaped structural block of rhyolite breccias and andesite flows lying between the Horne Creek and Andesite faults. The location of many of the individual orebodies in the Horne Mine was thought to be controlled by splays off the Andesite fault. A complicating factor in the Horne Mine could be that the gold ore zones and the VMS ore zones have different controls, and formed at different times. It certainly appears, from the description of Price (1949), that some of the gold ore zones were controlled by structures which cut across the base-metal massive sulphide ore zones.

A great deal of attention was paid to the relation of ore to diabase dikes. This was because major diabase dikes occur in three of the four large deposits which were known at the time (Horne, Amulet and Normetal), and two major dikes intersected in the largest of the deposits, the Horne Mine. From this empirical association, it was concluded that the mineralization and diabases were related. It was then reasoned that if the ore pre-dated the diabase, it was probably related to the latest Algonian granites in the area, which meant that these might constitute important regional scale, area selection criteria. Alternatively, if the ore post-dated the diabases, then it was probably related to the magma source of these dikes, which meant that deposits might be as widespread as the diabases.

In summary, according to the epigenetic replacement model for VMS deposits, the important area selection criteria were major fault systems, and permeable rhyolite breccia bodies in contact with impermeable basalts and gabbros. Very little emphasis was given to stratigraphic location, or to the details of the volcanic rocks in the mineralized areas, and their interpretation in terms of volcanic processes. Alteration was recognized as being closely associated with ore, particularly chloritic alteration. Diabase dikes were also thought to be important.

Syngenic Volcanic-Exhalative Model

In the mid- to late-1950s, the deposits of the Noranda area came to be recognized as part of a distinctive class of deposits found throughout the world which shared the common characteristics of being always associated with submarine volcanic rock sequences, and showing a strong element of stratigraphic control. The first serious consideration of stratigraphic position as an area selection criterion was probably by geologists working for Consolidated Zinc Corporation in the Noranda area in the mid- to late-1950s, under the influence of Haddon King, then chief geologist of Consolidated Zinc. King had become convinced of the importance of stratigraphic control from work on the Zn-Pb-Ag deposits at Broken Hill (King and Thompson 1953). This new stratigraphic emphasis led to the discovery by Consolidated Zinc of the Vauze deposit in 1957.

It was a short step from the realization that VMS deposits were dominantly controlled by stratigraphy,

to realizing that they were the product of the volcanism that produced the stratigraphic succession. Consolidated Zinc geologists had come to this conclusion by 1960, and by 1965 it was accepted by most of the explorationists working in eastern Canada (Hutchinson 1965; Suffel 1965; Roscoe 1965; Gilmour 1965). Interestingly, the acceptance of the importance of stratigraphic position as an ore guide was initially accompanied by a de-emphasis of the role of structure and the importance of alteration, perhaps in reaction to the previous domination of these features as area selection criteria (Figure 3.11).

It was not until the 1970s that the synvolcanic model entered the mainstream of academic thought, although similar ideas were developed and widely accepted in the mid-1960s by Japanese geologists working on the VMS deposits of Japan (Horikoshi 1969). Especially following the discovery of sulphide-depositing black smokers on the ocean floor, there has been much "re-inventing of the wheel" as features and concepts familiar to the geological community concerned with the deposits of eastern Canada and Japan were recognized by the largely non-exploration oriented geological community that now scrambled to restudy other ancient VMS deposits.

The presently accepted model for VMS deposits in Archean greenstone belts is that they are formed around the discharge vents of submarine hot springs in the tectonically active, high heat flow environment of felsic volcanic centers (Franklin *et al.* 1981). The environment is analogous to that of the majority of the high energy, high temperature subaerial geothermal fields associated with felsic volcanism (Hodgson and Lydon 1977). According to this hypothesis, two major principles underlie the interpretation of the descriptive features of the deposits:

1. Sea-floor hydrothermal activity develops at certain stages in the volcano-tectonic evolution of a volcanic complex, and is associated with a number of characteristic volcanic and tectonic effects which are reflected in the lithological and structural characteristics of the favourable stratigraphic zones.
2. Mineralization formed in and around sea floor hot spring discharge vents. These were structurally controlled loci of a variety of volcanic and hydrothermal effects ranging in age from pre- to post-mineralization.

The association of ore with rhyolitic breccias, recognized by early workers, is now attributed to one of at least three possible processes:

1. the formation of breccias close to structurally controlled magmatic vents, which also were hot spring vents

2. the origin of many of the breccias by hydrothermal explosive activity associated with the ore-forming event
3. the formation of breccias in association with a major volcanotectonic event, such as caldera formation followed by resurgent doming, with which the ore-forming hydrothermal activity was associated

The abundance of dikes in mineralized locales is considered to reflect the long-lived permeability of these structural sites to both magmas and ore solutions. Since the synvolcanic model allows for the possibility of post-ore, but still basically synvolcanic dikes, it is now realized that orebodies may be segmented by dikes, and occur as xenoliths in larger gabbroic masses. This has important implications for exploration, since orebodies may be concealed or offset by post-ore intrusions.

Both the epigenetic and synvolcanic models emphasize the importance of structurally controlled fluid conduits. However, while any structure with late movement on it is favourable by the epigenetic model, only structures present at the time of volcanism are favourable by the synvolcanic model. Thus, the synvolcanic model dictates that considerable effort is directed towards relating structures to the type and distribution of volcanic rocks, both as a means of tracing these structures by lithological mapping, and as a means of establishing their synvolcanic origin.

It is notable that the synvolcanic model led to the end of emphasis on diabase dikes in exploration. Yet it remains a fact that major diabase dikes are spatially associated with many, although certainly not all, of the important VMS deposits in the Canadian Shield. Two questions need to be answered to determine the extent to which it is appropriate to consider diabase dikes in VMS exploration:

1. Are diabase dikes more common in VMS deposits than in similar-sized areas without mineralization, i.e. is the association empirically significant?
2. Is there any plausible genetic reason for the association?

If the answer to question (1) is "yes", as it certainly was in the early stages of exploration of the Abitibi Belt, then it is appropriate to place at least some emphasis on diabase dikes, even if the answer to question (2) is "no". However, there is a plausible explanation for the association: the dikes may have been emplaced into long-lived, fundamental structures that controlled, at a much earlier time, the distribution of volcanic rocks and synvolcanic mineralization. Therefore, diabase dikes probably should be given some emphasis in exploration.

Through comparisons with active hydrothermal systems, different genetic types of hydrothermal alteration have been identified in VMS environments. It is now recognized that stratigraphically controlled

alteration, probably analogous to that produced by self-sealing in active hydrothermal systems, may be characteristic of the strata immediately below ore-bearing horizons (Hodgson and Lydon 1977; Sopuck *et al.* 1980; Gibson *et al.* 1983). Regional-scale zones of metal leaching and associated alteration may also be present in areas with VMS deposits (MacGeehan 1978). The recognition that alteration, mineralization, and volcanism can overlap in time and space has led to the possibility of identifying hydrothermal centres by tracing the distribution of transported clasts of altered or mineralized rock in volcanic breccias. The Fukazawa deposit in Japan was discovered in this way (Tanimura *et al.* 1974). Thus patterns of alteration and mineralization have become much more refined tools for orefinding than they were when the epigenetic model was dominant.

In summary, the synvolcanic model has led to an emphasis on the total volcanic environment of mineralization, as this can be interpreted from the types and distribution of volcanic extrusive and synvolcanic intrusive rocks and structures. In the future, it seems likely that there will be further refinements of the model which will enhance our ability to choose favourable sites for exploration on the basis of geology (*see* Figure 3.11). Stratigraphic position as a simple area selection criterion will be replaced by a more sophisticated set of criteria based on the details of the lithological association. These criteria will define what constitutes a favourable stage in the volcanic development of an area for the formation of an ore-forming hot spring system. Significant advances will also be made in our ability to identify the structures which are obviously so important in controlling volcanic phenomena on all scales, from the regional to the local. These advances will come as a result of improvements in our understanding of the structural framework of greenstone belts, and the relationship of geologically late to geologically early structures.

Exploration Methods in Relation to VMS Models

The use of available exploration tools must evolve in tandem with the changing character and emphasis on specific area selection criteria. Initially, all that could be done on an outcrop was to establish the presence or absence of mineralization. Now we search for a wide variety of features which are meaningful to the interpretation of the volcanic history of an area. This interpretation, in turn, influences our assessment of the area's potential for VMS deposits. Similarly, whereas once the goal of geophysical surveys was just to locate conductors, now there is an increasing use of EM, IP, and especially magnetic data to extend and enhance geological data as a basis for interpreting the total geological environment. The application of lithogeochemical techniques has advanced with increases in our understanding of the types and significance of altera-

tion associated with ore-forming submarine hydrothermal systems.

MODELS FOR ARCHEAN GOLD DEPOSITS

The situation with gold deposits is quite different from that of VMS deposits. Whereas the model for VMS deposits is well developed, and relatively few components which are important to exploration remain controversial, there is little agreement on the genetic significance of many of the features of gold deposits.

Magmatic-Hydrothermal Model: pre-1970

Gold was the main target of the Canadian exploration community during the first half of the century, especially during the period preceding the First World War when the great deposits of Timmins and Kirkland Lake were discovered, and the Depression years of the 1930s. At this time, the magmatic hydrothermal theory of ore formation was in ascendency in North America and it was generally accepted for gold deposits, without much controversy. According to the model (*see* numerous articles in the Canadian Institute of Mining and Metallurgy, 1948), hydrothermal fluids derived from "Algoman" granitoids moved up along major structures, like the major "breaks" of the Abitibi Belt, and deposited gold and associated minerals in structurally generated dilatant zones (Figure 3.12b). The porphyries so commonly associated with gold were viewed as manifestations of gold-related Algoman igneous activity, and also were thought to be structurally important in many deposits, providing a competency contrast with enveloping mafic schists which was favourable to the development of dilatancy during deformation. The concept of chemically favourable units was widely accepted, although the mechanical properties of rocks generally were considered more important than their chemical properties. For example, gold was thought to have been localized in the iron formations at Geraldton mainly because they behaved as brittle units, relative to the enclosing sediments (for review of ideas, *see* Macdonald 1984a).

Synvolcanic Models: 1970-82

There was a long period after the Second World War when little thought was given to gold, with the exception of the pioneering studies of Boyle (1961) in Yellowknife. The sudden renewal of exploration interest in gold, following the lifting of the price control by the US government in 1968, caught the geological and exploration community unprepared: very few government, company, or academic geologists knew anything about the geology of gold, in fact many had never seen a gold mine. Nevertheless, we were all quick to reject, out-of-hand, the prevailing classical magmatic hydrothermal model, with the disdain we typically reserve for all that is not new (and therefore, improved). It was perhaps predict-

ENVIRONMENTS OF PRIMARY GOLD DEPOSITION

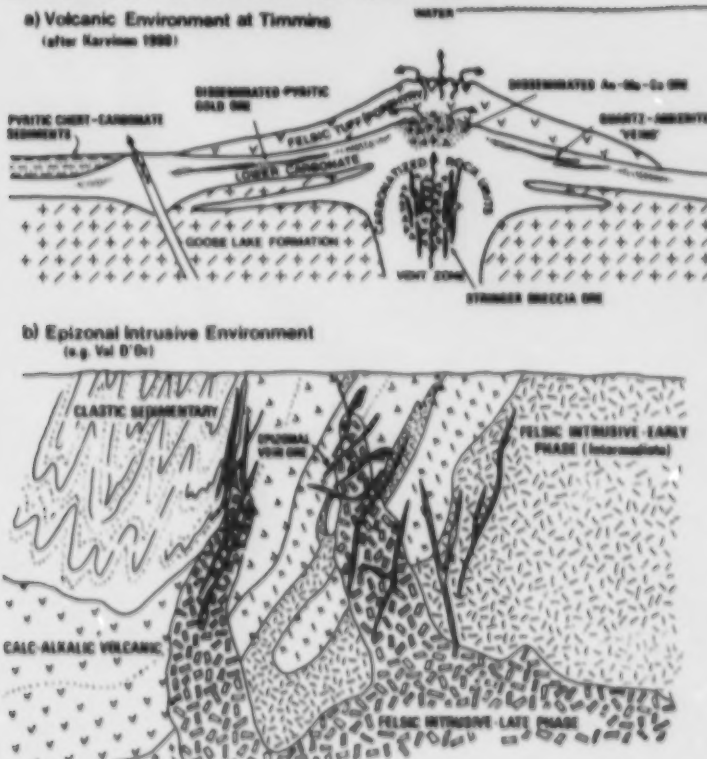


Figure 3.12. Models for primary gold deposition in the Superior Province (from Hodgson and MacGeehan 1982).

able that the model which had worked so well in massive sulphide exploration should be transferred to gold: the ideas were new, but were also familiar to most explorationists; they provided a number of clear exploration guides; they defined a clear role for geophysics, the major exploration tool in use at the time; and they made use of the stratigraphic data which had been the almost exclusive concern of geologists working in the greenstone belts in the previous decade. There was also a prevailing opinion that the magmatic hydrothermal model for gold did not provide an adequate explanation for some of the larger-scale features of the deposits, like their common association with ultramafic rocks, while it focused on explaining geological details. Similar "details", such as small veinlets of sulphide in dikes which blatantly cut across entire ore zones, had been major underpinnings of the epigenetic replacement model for VMS deposits, and were highly suspect as significant evidence in geological environments which had been subjected to metamorphism and deformation dating back to the Archean. Furthermore, the times were not propitious for those concerned with details; geology was undergoing a major revolution in basic concepts brought on by the new plate

tectonic theory, and geological arm-waving was the style of the day.

The new model for gold deposits (Ridler 1970, 1976; Hutchinson 1975; Karvinen 1978; Kerrich and Fryer 1979; Roberts 1981) explained the concentration of gold on the scale of individual deposits as primarily the result of sea floor and sub-sea floor hot spring activity (Figure 3.12a). Structurally controlled, epigenetic mineralization was interpreted as the result of remobilization, on the scale of individual deposits, during later deformation and metamorphism. As in the case with VMS deposits, many geologically complicated patterns of rocks and mineralization, previously interpreted as the result of complex structure, were reinterpreted as the result of synvolcanic processes: what had been structural truncations became stratigraphic pinch-outs; unconformities became facies changes; porphyry intrusions became intrusive-extrusive complexes; shear zones became tuff beds; banded veins and sulphide replacement zones in stratiform shear zones became auriferous exhalites; gold localized in competent conglomerate beds became metamorphically re-worked placer gold; and iron formations, previously

seen as structurally and chemically favourable hosts for late gold were widely re-interpreted as primary auriferous exhalites. Even the regionally extensive "breaks" of the Abitibi Belt were reinterpreted by some (Ridler 1970) as carbonate iron formations. A wide array of suitably modern (and generally little understood, by the average explorationist), chemical, isotopic, REE, structural, and volcanological arguments were found to support these new interpretations.

The influence on exploration of these changes in the gold model were profound. The effort which had previously gone into tracing favourable structures now was redirected into tracing what were deemed favourable stratigraphic sequences and horizons. Stratiform conductors in favourable parts of the volcanic stratigraphy were considered priority targets, irrespective of their structural environment, as were banded oxide iron formations. Carbonate alteration zones, now seen as favourable stratigraphic zones, were carefully re-examined for facies variations related to mineralization. In the Abitibi Belt, many obvious and long-recognized patterns in the distribution of gold, such as the restriction of all the large deposits to a zone within a few kilometres of the main breaks, were de-emphasized: if the gold was due to volcanism, why should not the area distant from the breaks be as prospective as those close to them, if the volcanic sequence was the same?

At about the same time as the exhalative model for gold deposits was being developed, there was a shift away from the magmatic hydrothermal to the metamorphic hydrothermal theory for the origin of the gold-bearing fluids (Pyfe and Henley 1973; Norris and Henley 1976; Kerrich and Hodder 1982). According to this latter theory, gold-bearing fluids are derived by prograde metamorphic dehydration reactions related to the initial stages of emplacement, during the waning stages of volcanism, of the granitoids which surround greenstone belts. Now that the epigenetic model has come back into fashion, metamorphogenic fluids are attributed to metamorphism caused by the emplacement of felsic magmas in the final stages of deformation and metamorphism of greenstone belts.

The metamorphic hydrothermal model reinforced the widely held idea that gold deposits do not occur in rocks of high metamorphic grade or in deep-level granitoids, by "explaining" their supposed absence in terms of gold mobilization during prograde metamorphism. Yet many large deposits occur in the granitoids bordering greenstone belts in Zimbabwe, and the super-giant Kolar deposit of India is hosted by rocks of the amphibolite facies (Hamilton and Hodgson 1986). This model unquestionably had a significant influence on geologists examining the Hemlo deposit in the days before the main ore zone was discovered. Indirectly, it provided support for the idea that Hemlo is a totally different type of gold deposit, implying that different

area selection criteria have to be used in the search for new Hemlos. This, in turn, has produced a tremendous amount of unproductive exploration in areas not previously considered prospective for gold.

The metamorphic hydrothermal hypothesis has resulted in a de-emphasis of the importance of porphyries, which can only be explained, in terms of this model, as accidental or secondary features of the gold-bearing environment, perhaps indicative of a structural environment of enhanced permeability to fluids and magmas. Whereas the magmatic hydrothermal hypothesis leads to an emphasis on the importance of spatial relationships between gold and magmatic hydrothermal deposits such as Mo deposits (Macdonald 1984b; Burrows *et al.* 1986), these patterns tend to be explained as fortuitous or of secondary importance in the metamorphic water hypothesis.

Recent Epigenetic Models

In the past five years, there has been a major swing back to traditional views of gold deposits being epigenetic, structurally controlled, and late in the geological development of greenstone belts. However, many of the genetic problems are unresolved, for example, the source of the gold, and the fluid from which it is deposited. At present, the main battle is between those who profess a magmatic origin for the ore solution, and those who profess a metamorphic origin. As a consequence, there is a wide diversity of opinion on which are the important criteria for exploration area selection for gold, and where the best ground to explore is located.

CONCLUSIONS

It is concluded that models are always with us, even if their existence is denied. Therefore the issue is not "model versus no model" but "good versus poor model". Models for ore deposits embody the descriptive characteristics of the deposits, and the larger ore-bearing geological environment. As such, models contain the descriptive data used to select areas for exploration during the exploration process, which involves progressively homing in on the most prospective parts of a region in a series of discrete steps. Good models are based on a full knowledge of the deposit population characteristics, interpreted in the light of the best geological theory. This interpretation is essential to rating, in terms of their probable importance and reliability, the descriptive features of the model which are used as criteria for exploration area selection. The function of geological research applied to exploration is to develop an understanding of how mineral deposits form, so that the genetic significance of the characteristics of ore deposits is understood. An important, and very much understudied aspect of mineral deposits is the relation of economic quality and geological features of deposits. Although much of exploration involves gathering geophysical and geochemical data, it should be em-

phasized that these data are useful only in that they reflect geological features which are area selection criteria for the deposit type being sought.

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4. Uncertainty and Risk in Exploration

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ABSTRACT

The mining industry in recent years has become increasingly averse to risk as a reaction to falling metal prices. Exploration programs driven by the need to renew mining company resources have given way to a more immediate profit-orientated mineral search.

Mineral exploration is now geared to a market which requires primarily open pit gold deposits amenable to rapid development, and high-grade polymetallic orebodies in order to improve the probability of commercial success.

In field operations, risk is reduced by optimizing every stage from land acquisition to drilling, and, in particular, by measuring a wide range of geochemical and geophysical parameters, exploring in terrains with potential for more than one ore type, and by avoiding unnecessarily sophisticated geological theory.

Exploration funding should not be dependent on short-term price fluctuations.

INTRODUCTION

Mineral exploration, like any other commercial venture, involves investment of money in the hope of future reward. Where it differs from most industrial enterprises is in the comparatively high risk of failure and the corresponding potentially high return.

In a mining operation, analysis of commercial risk is essentially the quantification of uncertainties related to capital and operating costs, product price, and market. At the exploration stage, in addition to these uncertainties are the unquantifiable risks due to a fundamental lack of understanding of the processes of ore deposition and the ambiguity of geological, geophysical, and geochemical information.

Mining districts in which there has been a long history of exploration and mine discovery, may have sufficient data from which the average discovery cost per ton of ore can be estimated and future success extrapolated (Mackenzie 1981).

This information is particularly valuable for government planning of new infrastructure and drafting of incentive schemes such as soft loans, grants, and flow-through shares. For such predictions of future discoveries to have any meaning, there must be a sufficient record of money spent and a statistically valid number of mines discovered.

Provinces such as the Canadian Abitibi Belt or the Great Basin of the United States, for example, have sufficient records either published or readily

estimated which could provide an adequate data base to calculate average success rates and costs.

Other ore districts are less predictable. Even if uranium exploration returned to its previous high level of activity, it would be unreasonable to expect discoveries of the large vein-unconformity ore deposits at the same rate as the late 1960s and the 1970s when the type was first recognized, and the obvious radiometric targets such as Ranger, were drilled.

Many deposit types have such a sporadic rate of discovery that forecasting the rate of future success, even on a regional basis, is very uncertain. The Swedish Lower Proterozoic Svecokarelian Province, for example, is spectacularly mineralized, but it is unlikely that any Swedish expert would be willing to predict when the next Falun or Boliden will be discovered. For the same reason, forecasts of future polymetallic mines in the Tasman Geosyncline, Australia, the Balmat-Edwards district, USA, the Iberian pyrite belt, or the Appalachians of the USA and Canada, to mention a few provinces at random, would be very unreliable.

At the level of the individual company, forecasting of future rates of success or exploration costs per unit discovery is particularly risky. Even for the most successful explorer, success is patchy, for in the long time scale necessary in exploration, staff, management, technology, and target minerals may change to such an extent that past performance may be irrelevant to the future.

The purpose of this paper is to review briefly the nature of risk in exploration, particularly in the present environment of uncertainty and change, and to outline how modern exploration companies are optimizing exploration success in their choice of minerals sought, selection of target exploration terrains, underlying geological concepts, and field procedures.

RISK AND UNCERTAINTY

The value of an individual exploration project is a function of the probability of discovering an ore deposit.

If this probability could be accurately estimated, then exploration risk could be minimized by concentrating exclusively on those projects with the highest chance of success.

In the real world, exploration properties are usually only evaluated quantitatively when they are sold or farmed out or, when they are part of a stock ho-

tation. Historic cost of the project is the usual base for payment in a farm out, with or without a premium, depending on the perceptions of the buyer or avarice of the seller. This makes sense in a situation where the owner is presenting the historic cost as reflecting the effort made to progress the project towards a producing mine. The incoming partner must therefore contribute at least in proportion to his share of the joint effort.

Historic cost, however, has very little relation to the true value of a property and is simply a convenient means for the buyer and seller to fix a price. Failed projects have their highest book value when they close.

A closer estimate of value is what the market will pay for the property in an outright sale. However, because of the basic uncertainties of exploration, there is no valid quantitative method of assessing the value of a project until a resource has been outlined and probabilities of economic grade, tonnage, favourable metallurgy, continuity, extraction costs, and so on, have been estimated and used to calculate its economic viability, present value, and accumulated risk. Up to this point, the valuation depends on subjective attributes such as "favourable geology", "encouraging" drill results, and "good" geochemical geophysical anomalies, which may vary with the bias or experience of the purchaser. In practice, the price paid for exploration properties is usually a closer reflection of the money available than of any intrinsic value.

The ultimate criterion of exploration success is finding mineable deposits. Before an exploration program has been completed, the quantitative probability of discovering an ore deposit is unknown. The value of the program therefore can only be assessed by judging to what extent risk is minimized in every aspect of the work. There is no objective quantitative method of estimating the value of an exploration project which can only be properly evaluated in relation to other projects as being more or less risky. Frequent discoveries of small or otherwise uneconomic deposits do not necessarily indicate that exploration is on the right track; it may have quite the opposite significance.

All aspects of exploration from land acquisition onwards are theoretically designed to optimize the probability of finding ore. The remainder of this paper will discuss briefly some areas of modern practice in which new risks are being introduced and where new techniques may optimise success.

The underlying uncertainties of mineral exploration are caused primarily by a fundamental lack of understanding of the processes of deposition of ore and the ambiguity of much geological, geophysical, and geochemical data. In recent years, uncertain or low metal prices and the threat of substitution by new materials have added to the risks and have in-

troduced a disincentive to exploration for some metals. Low profits have also resulted in reduced budgets. Sporadic funding of exploration depending on profits is inefficient, and for those with steady nerves constant exploration budgets over several years provide the necessary time to establish good management and field practices.

GEOLOGICAL UNCERTAINTY

Most modern exploration is based on a preconceived notion of the geological setting of the orebody being sought. At its simplest, this approach is identical with that of prospectors back to Roman times and beyond, who certainly recognised hydrothermal alteration, shear zones, and probably stressed vegetation patterns.

The underlying assumption is that once the favourable geological setting has been defined, then in order to increase the probability of success, exploration is concentrated in these settings and unfavourable geology is eliminated from the search.

The validity, or otherwise, of a particular geological theory in a current exploration program is particularly difficult to assess objectively. Geologists tend to be almost emotionally devoted to favourite concepts and in the heat of the search find it difficult to stand back and review alternative hypotheses. Because exploration success can only be judged in the long term, there is a risk that a false geological concept may be followed in spite of exploration failure, on the grounds that it has had insufficient time to be tested. The effect of geological theory in exploration for two ore types—"sediment-hosted copper" and "vein unconformity uranium"—is described below. These have been selected because they are not the current focus of intense exploration and may therefore be reviewed with some detachment as "case histories" of the application of theory to the reduction of exploration risk.

Sediment-hosted Copper

The Central African Copperbelt represents the largest concentration of deposits of this type. Several mines, particularly Bwana Mkubwa, Chambishi, and Kansanshi, were already known and worked by the local inhabitants before the arrival of British mining companies in the beginning of the twentieth century. The first geological reports were unanimous in their interpretation of the copper mineralization as epigenetic related to emanating hydrothermal fluids from intruded granites (Gray 1929). Subsequently, Garlick (1940, 1941) recognised that the granites were older than the surrounding sedimentary rocks on the basis of his detailed mapping of the contacts, particularly granitic apophyses in underground exposures which he re-interpreted as weathered slabs of onion-skin weathered rock still in contact with the granite outcrop, but rotated outward and surrounded on all sides by sedimentary rocks.

This important step in understanding the geological relationships in the Copperbelt lead to Garlick's proposal that the Zambian copper mineralization was deposited at the same time as the sediments in a process similar to that proposed by Geikie (1893) and Schneiderhohn (1932). Binda (1975) and Clemmey (Member of the Geological Society of London, personal communication, 1984) provided support to Garlick's view that copper was derived from an eroded source and carried both in solution and as mineral particles to the sea.

Davidson (1965) proposed that deep interstitial brines leached, transported, and concentrated low-grade copper mineralization in the Kupferschiefer. Renfro (1974) suggested a more elaborate process of transport of copper in solution by seaward migrating brines in a coastal sabkha environment. This theory neatly explains the stromatolite association with copper at Mufulira, but is difficult to reconcile with the high energy sand depositional environment at Chibuluma for example.

Van Eden (1974) proposed that copper was transported from basin sediments by dewatering in a process similar to oil migration. In his view, the initial concentration of copper in the sediments is irrelevant, and it is the scavenging efficiency of the migrating brines and the effective precipitation of the copper in porous sediments on the basin margin

which determine the formation of the copper orebodies.

In similar deposits, such as Udokan and Dzhezkazgan in the Soviet Union and the Kupferschiefer of Poland, there is also a wide range of opinions on their origin, from Chukrov (1972) who proposed a biogenic sedimentary origin at Udokan; Narkelyun and Yurgenson (1968) who reported that the consensus among geologists in the Dzhezkazgan district was that the metals were derived from the erosion of Precambrian to Paleozoic sedimentary rocks and intrusive rocks to the north; and Bakun *et al.* (1966) who derived the Udokan copper in a similar way from the Aldan Shield. Krashenninnikov (1964) described the Dzhezkazgan district as "of sedimentary origin" but subjected to redistribution by diagenesis and epigenesis.

Ensign *et al.* (1968), Metzler (1975), and Annells (1984) agree on the importance of mafic volcanic rocks as a source for the copper at White Pine in the Kupferschiefer, and the Zambian Copperbelt.

Out of the vast amount of literature on sedimentary copper ore genesis briefly summarized in Table 4.1, I believe it is fair to say from the hindsight of 1987, that mafic plutonism and associated rifting are the key elements in this ore type. Most of the genetic theories published until the late 1970s either identify environments such as proximity to basement

TABLE 4.1. LITERATURE ON SEDIMENTARY COPPER ORE GENESIS.

Author	Deposits	Genesis
Geikie (1893)	Kupferschiefer	Syngenetic
Gray (1929)	Copperbelt	Hydrothermal from granite
Schneiderhohn (1932)	Kupferschiefer	Syngenetic
Garlick (1945)	Copperbelt	Syngenetic from basement
Krashenninnikov (1964)	Dzhezkazgan	Syngenetic with diagenetic remobilization
Davidson (1965)	Kupferschiefer	Concentration by deep brines
Ensign <i>et al.</i> (1968)	White Pine	Epigenetic from mafic volcanics
Clemmey (1984)	Copperbelt	Syngenetic from porphyry in basement
Narkelyun and Yurgenson (1968)	Udokan	Syngenetic from basement
Obers and Sorkins (1968)	Kupferschiefer	Syngenetic from basement or mafic volcanics
Bakun <i>et al.</i> (1966)	Udokan	Syngenetic from basement
Chukrov (1972)	Udokan	Syngenetic from basement
Lau'Ye and Gehlins (1972)	Kupferschiefer	Diagenetic
van Eden (1974)	Copperbelt	Basin de-watering
Renfro (1974)	Copperbelt	Sabkha
Metzler (1975)	Kupferschiefer	Syngenetic from mafic volcanics
Salikhov (1976)	Udokan	Syngenetic with diagenetic remobilization
Annells (1984)	Copperbelt	Diagenetic ? from mafic volcanics

highs, already known to be favourable, or lead to the elimination of ground on the basis of false criteria.

That is not to say that once a sedimentary copper province has been discovered, that sedimentary traps, such as sabkhas for example, may not be found to be important focuses of mineralization; but that the prime cause of ore deposition was magmatic and tectonic. It is these characteristics which are fundamental in the selection of exploration targets.

It is no exaggeration to conclude that most scientific theories for the origin of sedimentary copper deposits have had either no effect on the overall risk of exploration or may have added to the risk by attaching undue significance to irrelevant geological settings.

Vein-unconformity Uranium

The world's largest reserves of economically exploitable uranium are situated at the unconformity of Middle Proterozoic continental sandstones on Lower Proterozoic metamorphosed marine sediments. The Rum Jungle and South Alligator districts of the Northern Territory of Australia and the Athabasca basin deposits of Saskatchewan, Canada, are strikingly similar geologically and contain most of the deposits of this type. Oklo and Mounama in Gabon, and Kitts - Michelin in Labrador, Canada, are probably related types (Nash 1981), together with the uranium occurrences in the Araxá Group, Goiás, Brazil.

Nash (1981) has summarized the characteristics of the ore type as being near to the Lower Proterozoic/Middle Proterozoic unconformity; near an Archean granite-gneiss basement block; in or near graphitic schist, biotite-garnet schist, and dolomite marble representing original marginal marine facies sediments; and in a fault zone with associated chlorite alteration.

The similarity in detail of the Pine Creek Geosyncline and its overlying Kombolgie sandstone in Australia to the Wollaston Fold belt and Athabasca sandstone of Saskatchewan is so close that it is inconceivable that the uranium deposits in both provinces were formed by different processes.

Hoeve and Sibbald (1978) argued that the uranium at the Rabbit Lake Deposit in Saskatchewan was transported in solution along the basal contact of the Athabasca sandstone and fixed by a cloud of methane gas derived from the hydrothermal alteration of Lower Proterozoic graphitic siltstone.

Binns *et al.* (1980) and Ewers *et al.* (1983) have proposed that uranium in the South Alligator deposits was derived from Archean and Proterozoic granites older than the Pine Creek geosyncline sediments which host the ore. The granites would also have provided heat to generate convection cells which leached uranium from the granite and trans-

ported it upward to be precipitated in the open space and favourable chemical environment provided by the graphitic siltstone and carbonate host rocks.

Tisley (1978) has made the ingenious proposal that the dominant concentration mechanism is a process of migration of positively charged uranium complexes in solution in groundwater under the influence of a potential gradient of a natural electric cell produced by the graphitic siltstone.

Crick and Muir (1980) derived the uranium from the Archean basement from which it was leached and transported by connate waters and groundwaters to be deposited in a marine evaporite basin by a sabkha process. Water released from the conversion of gypsum to anhydrite, and meteoric water, subsequently redissolved the uranium, transported it to open spaces in the carbonate rocks where it was precipitated, and concentrated. Chlorite associated with the uranium mineralization would be produced from iron and magnesium transported together with the uranium.

While these diverse theories represent important contributions to the science of ore deposition, they contribute little to the business of exploration. To assume that Lower Proterozoic sabkhas, granitic intrusions, or uranium-enriched Archean basement are essential for the formation of vein-unconformity deposits, would increase the risk of exploration failure. Equally, it is difficult to see how the argument for precipitation by methane gas would help in the Northern Territory of Australia where the deposits are hosted by the Lower Proterozoic metasedimentary rocks and not the Middle Proterozoic sandstones as in the Athabasca Basin deposits.

Dahlkamp (1987), in his classification of uranium ore deposits, refers to Jabiluka, Ranger, and Olympic Dam as "veinlike" and Key Lake, Rabbit Lake, Cigar Lake, and Chuff Lake as "unconformity" type. There may be good scientific reasons for classifying Ranger with Olympic Dam, but from a pragmatic viewpoint the Australian and Canadian vein-unconformity type uranium deposits represent a discrete ore type with their own specific geological setting and appropriate exploration methods. The Stuart Shelf is a very different exploration environment to the Pine Creek Geosyncline.

A more objective non-theoretical analysis of the vein unconformity uranium deposits leads to a more rewarding conclusion. The chemistry of the vein-unconformity deposits is unusual in comparison with most uranium ore types. Gold is a common constituent of both the Canadian and Australian orebodies, and, in addition, the Athabasca Basin mineralization contains anomalous selenium, copper, cobalt, and nickel.

Dahlkamp has reported up to 30 percent nickel at Key Lake, and high-grade cobalt mineralization occurs throughout the Wollaston Domain. Chuff Lake contains anomalous silver and platinum group elements (Hoeve and Sibbald 1978).

The deposits of the El Sherana district in the Australian Pine Creek Geosyncline have a similar chemistry to those of the Athabasca Basin. Threadgold (1960) has described paragenetically early nickel and cobalt arsenides and sulphides followed by pitchblende and finally by an assemblage of iron and copper sulphides, nickel selenide, galena-clausenthalite (PbSe), and gold. Clausenthalite is known to contain platinum from an occurrence in the Harz Mountains (Ford 1966).

The Coronation Hill platinum-palladium-gold discovery by the BHP - Noranda - EZ joint venture in the El Sherana district (Anonymous 1987) is therefore unexceptional, considering the chemistry of the area, and is predictable from the known chemistry of vein-unconformity and related deposits. Published theories of ore genesis, however, would not have led to the discovery of this new and significant ore type.

The development of theories of genesis of other ore types such as Mississippi Valley lead-zinc, volcanogenic copper-zinc and gold, and shale-hosted lead-zinc-silver have progressed in a similar way to the two examples given and the same conclusion applies that the underlying lack of knowledge of the processes of concentration of ore minerals is so great that many plausible theories can be constructed seemingly to fit the facts, but few can be shown to be successful in predicting new ore deposits. Exploration strategies based on such theories compound the underlying geological risk of failure with the additional uncertainty that the assumptions of favourability or otherwise of geological settings may be incorrect.

An unstructured review of available data not biased by genetic theory may identify new ore types which would not be predictable on theoretical grounds.

Suspicion of new scientific theories should be ingrained in the exploration industry. Because the science of geology is so uncertain, glib and plausible hypotheses can be constructed by fertile academic minds and sold to unsuspecting exploration managers as the final answer to their prayers, often with disastrous results.

However, conservatism may itself increase risk if it results in rejection of important predictive theories. Geikie (1893) is referred to above for his reference to syngenetic sulphides. In the same publication, he also quotes several authorities from the mid-nineteenth century in support of his view that Nevada gold deposits were formed by a process of transport and deposition by hot spring water. This is a particularly good example of the slow progress of a now widely held theory with application in exploration.

It is for the exploration manager to decide to what degree exploration is influenced by theory, and possibly to design a program based on several differ-

ent hypotheses, or alternatively, to reject all theory for a purely pragmatic approach. The current gold exploration boom in the US Great Basin represents a successful example of the latter.

Where the science of geology assists most in improving the commercial risk of exploration is in increasing the data and information which provide the raw material from which decisions, from selecting new ground to siting drillholes, are made. This data and information is obtained mainly from field observations presented as geological maps by high calibre, well-trained geologists. The competence of field geologists is fundamental and probably the single most important positive influence on geological risk. It is ironical that the industry generally depends on its least experienced geologists to provide the raw data.

Geological mapping and interpretation often assume some regional model such as the relationship to a subduction zone or location in a sedimentary basin within which the stratigraphy, intrusive relationship, or other rock associations are placed. Interpretation of a terrain or prediction of sub-surface geology contain the risk that this geological model is incorrect. For decision making in exploration, it is important to know how sensitive the geological interpretation is to those different conceptual models. The recording therefore of unbiased geological observations as "fact maps" is an essential, but unfortunately far from universal field practice.

It is particularly important in mapping allochthonous terrains that the regional geological model should not put together artificial associations across major breaks. Brew *et al.* (1985) and Gehrels and Berg (1984) in their mapping in southeastern Alaska, for example, have been careful not to extend stratigraphic correlations more than is geologically prudent. The result is clumsy geological maps with a patchwork of fault-bounded blocks of overlapping ages containing a varying proportion of sedimentary and volcanic rocks. However, this judgement of the limits of correlation is important in defining the area of exploration for stratigraphically controlled base and precious metal mineralization. The recognition of the allochthonous nature — if true — of the terrain, no matter how untidy the map, contributes significantly to reducing exploration risk. Orogenic belts are clumsy structures.

A further means of reducing the underlying geological risk of failure in exploration is by exploring in terrains which contain more than one potential ore type. The geosynclinal terrains of Eastern Australia, the Appalachians, and the American Cordillera, for example, contain both high grade base metals and polymetallic mines such as, Rosebery and Buchans and at least potential for hydrothermal gold of the Juneau, Hope Brook, or Ballarat type.

In summary, the underlying geological risk of mineral exploration may be reduced by careful high quality field observations, avoidance of unsubstantiated ore genetic theories and geological models,

and concentration in geological environments containing a variety of potential ore types.

GEOPHYSICS

Geophysics in modern exploration has the function both of directly finding ore deposits because of some detectable physical characteristics, and of assisting in the interpretation of geological maps. In both these roles, the interpretation of geophysics is most effective when combined with geological and geochemical information to produce the best fit of all the parameters which are indicative of a particular ore deposit or geology. Computer modelling is also fundamental in this interpretation, and by reducing the number of possible dimensions and orientations in space of the putative ore deposit or geological unit, may assist in the siting of drillholes. New equipment such as the EDA combined VLF-magnetometer-gradiometer OMNI PLUS system, and the Scintrex IGS integrated magnetometer-VLF-horizontal loop EM, enable the operator to accumulate a large range of physical parameters in one operation at a relatively low marginal cost compared to a conventional survey.

Hydrothermal alteration systems associated with structurally controlled gold deposits, commonly characterized by magnetic depletion, increased resistivity due to silica alteration, or high conductivity in clay zones, are particularly appropriate targets for these systems.

The data of at least one day's survey is stored in the field in the instruments own memory, and magnetic data may be reduced overnight by "mating" with a base station and be available for immediate plotting and interpretation.

New processing software enables digital data to be presented in various ways to enhance weak anomalies and trends which may be overlooked by conventional analysis. Other advances in geophysical equipment which increase confidence in the acquired data are improved navigation by high resolution radio positioning and increasing sensitivity in instrumentation.

Further integration of geophysical, geochemical, and geological information at a relatively low marginal cost is obtained by borehole geophysics — both logging and downhole EM.

The new geological targets of base metal, massive sulphide deposits, and fracture-related hydrothermal gold within the same area and geological terrain already mentioned above, require airborne EM to locate both deeply buried, highly conductive massive sulphides, and mineralized shears. A combination of VLF, and frequency domain EM with a range from 1000 to 10 000 Hz is the most appropriate specification both for this range of targets and for surface and subsurface mapping. Time domain EM should also cover a wide band including short delay times.

Airborne spectrometry is increasingly being recognized as a valuable geophysical technique, particularly in regional mapping, but also for identification of potassic alteration in the K channel.

Figure 4.1 shows the relationship of gradient array IP chargeability and ground K channel spectrometry to geology and the projected position of the Cabaçal hydrothermal gold deposit to illustrate the use of spectrometry in identifying alteration and the integration of geophysics with geology (Barreira 1987).

Zinc-rich polymetallic deposits, increasingly the main target of base-metal exploration (*see Metal Price below*), commonly have at best a weak EM signature which may be recognizable only by more sophisticated massaging of the EM data.

Developing techniques in spectral IP and airborne gravimetry would contribute significantly to exploration, should they become operational, by adding new physical parameters to assist interpretation. Ground gravimetry is already an important technique in exploration and contributed significantly to the discovery of the Olympic Dam Deposit (Anderson 1980) and to several of the Iberian Pyrite Belt, massive sulphides, including Neves Corvo (Strauss *et al.* 1977, Carvalho 1981). The cost of gravimetric surveying is the biggest restraint on its use as a complementary technique to magnetometry and EM. An airborne gravimetric system which could discriminate the response from targets as small as most ore deposits would have great exploration value.

The integration of several geophysical techniques, each measuring a broad band of parameters together with geology and multi-element geochemistry, provides the best technical means of reducing exploration risk.

GEOCHEMISTRY

Modern exploration geochemistry involves the sampling and chemical analyses of a variety of materials from rocks to stream sediments, soils and plants, and the identification of "anomalous" values in the metals sought or in associated elements. An "anomaly" may be negative, such as the silica depletion in French uranium granites or the carbonate loss in Great Basin gold deposits of the USA. The underlying risk is due to the uncertainty of the deposit having a recognizable, characteristic primary chemistry in its wall rocks or in the secondary dispersion environment which is dependent on a large number of variables. In addition, there is also no certainty that an anomaly, even where it exists, will be detectable.

To optimize the probability of success, it is fundamental that a geochemical survey be planned to cover the search area with a statistically adequate sampling density, and individual samples taken to be as representative as practically possible of the medium.

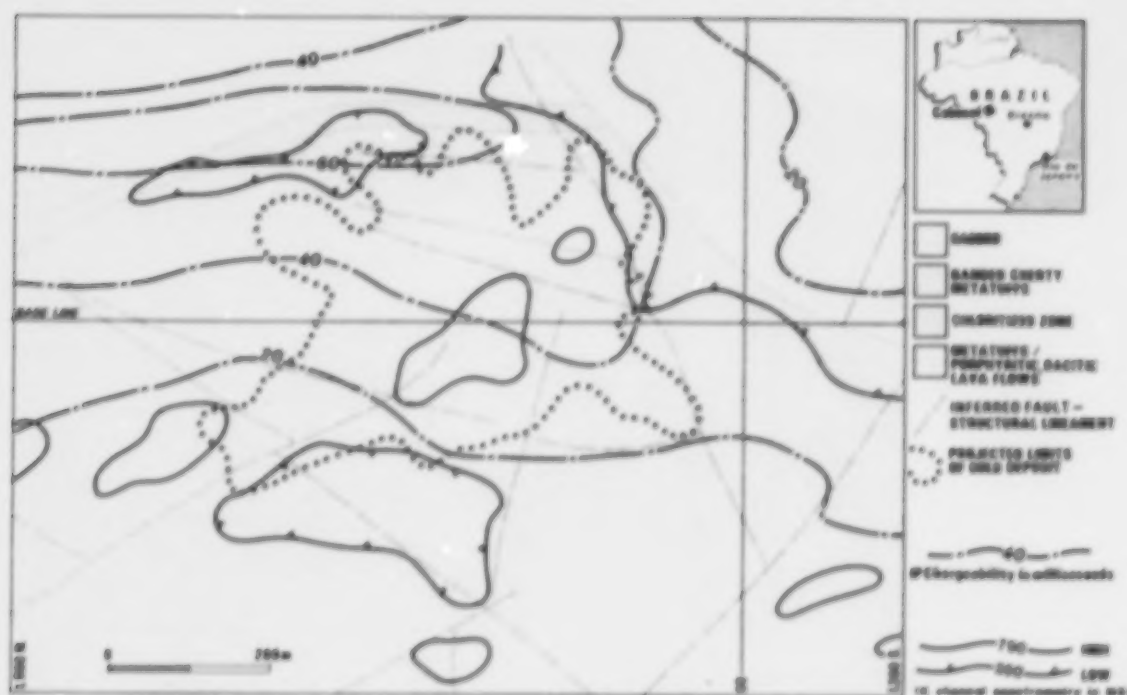


Figure 4.1. Cabeçal I. (Mato Grosso) (Barreira 1987).

In the interpretation of geochemical data, the main objective is the identification of anomalous values which may be related to ore mineralization. Standard deviation as a measure of the significance of anomalous geochemistry is now recognized as being purely arbitrary.

The processes of transport and deposition of metals in the natural environment, both in the formation of ore and in subsequent weathering, may cause chemical changes in the surrounding rocks characteristic of the particular ore-bearing fluid which may produce a typical rock chemistry and alteration.

Elements which individually are not statistically anomalous, and which fall within the background density distribution, may be significant indicators of ore mineralization when taken with associated elements. Multi-element geochemistry may therefore provide a distinctive and less ambiguous pattern of ore chemistry than high values in one metal.

The interpretation of multi-element geochemistry has been the subject of a great deal of work in the Soviet Union demonstrated by various publications in the 1960s and summarized by Beus and Gregorian (1977). With the development of cheap multi-element analysis and computer-based data handling, these techniques are increasingly relevant.

Figure 4.2 illustrates the enhancement of anomalous Bi, Cu, Co, and W when their normal-

ized scores are added and plotted as contoured "background units". The effect of random error is reduced by increasing the number of elements and in the ideal case, the ratio of the additive anomaly to the background noise, which is a measure of its intensity, is a function of the square root of the number of elements added.

If the pattern of the chemistry of the ore host rocks is known, a ratio of the additive chemistry of elements with a tendency to accumulate above the ore to those below the ore, will have the effect of enhancing the response where this pattern occurs. Where there is no systematic zonation of this type, the ratio will be random. Beus and Gregorian (1977) referred to this ratio as the additive index. Figure 4.3 illustrates the different additive index response from an orebody and from rocks with anomalous geochemistry with no known ore association.

There is a vast research potential for using more sophisticated techniques of pattern recognition in geochemistry.

In recent years, the cost of putting a well-trained sampler in the field has increased, while the cost of chemical analysis has fallen in real terms. It is therefore increasingly cost effective to analyse for a large number of elements.

The logic of accumulating multi-element analyses to enhance a geochemical anomaly applies equally to its integration with geology and geophys-

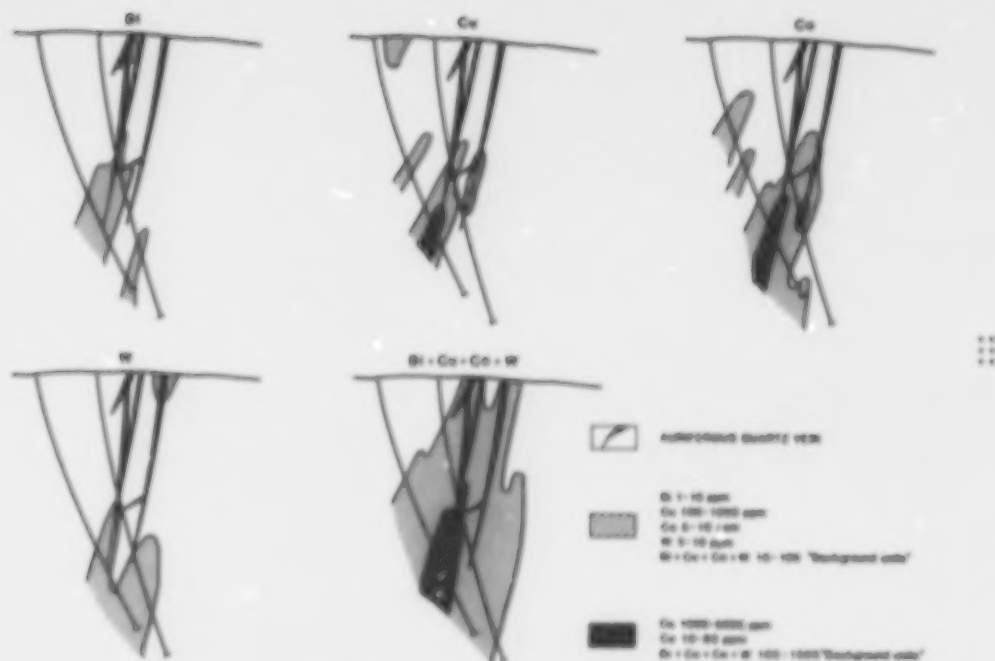


Figure 4.2. Enhancement of primary geological haloes around a gold deposit by additive geochemistry (Beuss and Gregorian 1977).

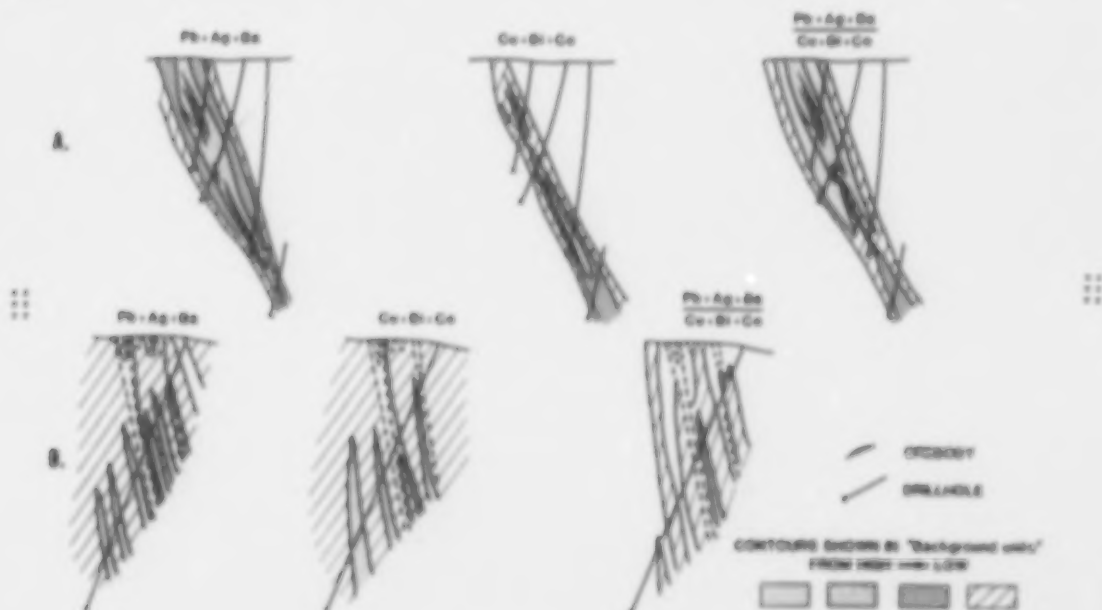


Figure 4.3. Comparison of primary geochemical haloes in polymetallic orebodies in eastern Kamchatka (A) with un-economic dispersed mineralization in Kyshtash-Kokchegirsk (B) (Beuss and Gregorian 1977).

ics. The risk of a spurious anomaly is reduced when it is confirmed by independent observations of other physical characteristics. The optimum drill target has the best fit of all recorded data.

METAL PRICE

Forecasting metal prices is a notoriously uncertain business. Figures 4.4 and 4.5 illustrate predictions

EXPLORATION '87 PROCEEDINGS
THE ROLE OF EXPLORATION IN RESOURCE DEVELOPMENT

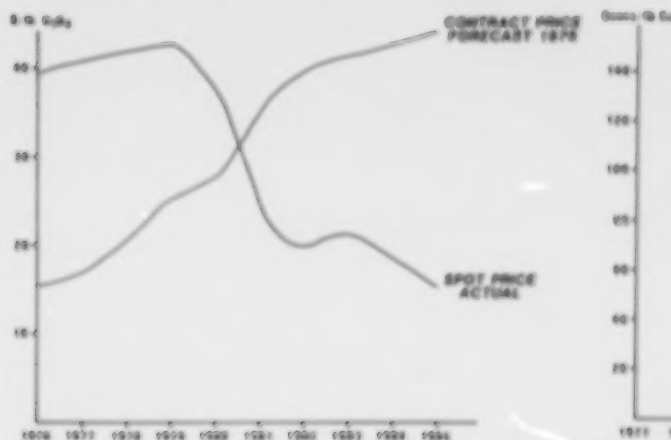


Figure 4.4. Uranium price forecast - 1976.

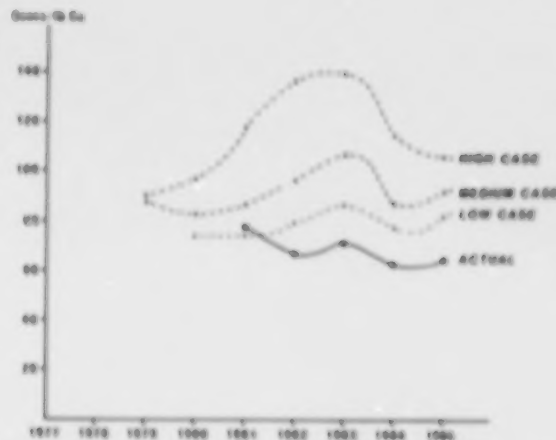


Figure 4.5. Copper price forecasts - 1979.

by highly reputable experts from the 1970s, of the future price of uranium and copper. The forecast made in 1976 of the 1987 uranium price was 200 percent higher than actual. The low case copper forecast was 25 percent, and the high case 80 percent higher, taken as an average yearly price over the same period. These examples are in no way exceptional and far more spectacular errors exist in published literature. Other metals, particularly nickel, tin, and silver show a similar disparity between hopes and reality.

The period over which these prices were taken is probably exceptional in that it is improbable that the shakeout in base metals and uranium, in the late 1970s and 1980s, will be repeated in the near future. However, the message is that in the time frame

of exploration to production, unanticipated events may have a disastrous effect on price.

The response of the mining industry to low metal prices has been to reduce costs in order to remain profitable, and to pass on the problem to exploration in the requirement for higher grade deposits. The present attitude of mining companies is reflected in the grades of polymetallic ore deposits at feasibility and pre-production in 1976 (Table 4.2), as compared to 1987 (Table 4.3). While the average value of contained metal per ton is virtually unchanged in 1987 dollars (Figure 4.6), the grades compared to 1976 are significantly higher, zinc by 60 percent (Figure 4.7), copper by 45 percent (Figure 4.8) and precious metals by 18 percent, as compared to 1976. This is the nature of the market place which sets the targets for mineral exploration in the late 1980s.

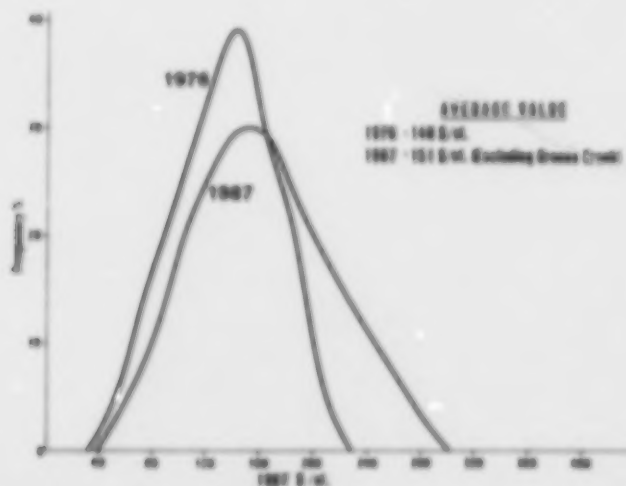


Figure 4.6. Advanced polymetallic projects Comparison of Ore Values.

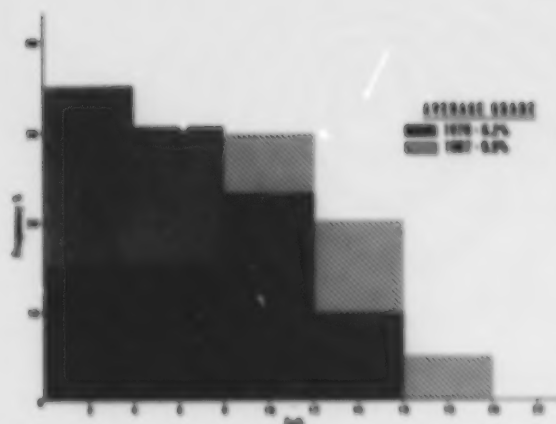


Figure 4.7. Advanced polymetallic projects Comparison of Zn Grades 1976-1987.

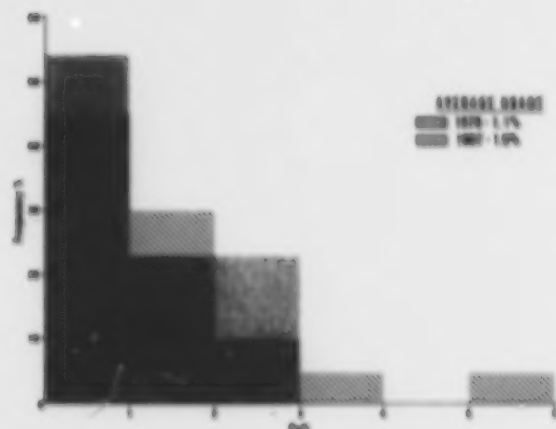


Figure 4.8. Advanced polymetallic projects Comparison of Cu Grades 1976-1987.

The exploration risk in base metal and base-metal dominated polymetallic deposits has therefore increased since 1976 due to the demand for higher grades. Furthermore, as the copper price has fallen in real terms more than zinc, and because of the large overhang of potential copper production, the industry prefers zinc-rich deposits. Because of the low conductivity of sphalerite, these are generally poorer targets for electromagnetic exploration methods, and are therefore less amenable to discovery.

While the uncertainties of future price still apply to base metals, it is improbable that there will be a further price collapse. Declining prices in the 1980s had the effect of pushing down operating costs to the point where profit margins have been squeezed or lost. There is little room left for further cost reduction and it is generally felt in the industry that base-

metal prices have reached a support level at least in the short to medium term. However, in the long term, new technical ceramic materials represent a serious challenge.

Precious metals, on the other hand, are exposed to the risk of a price fall because of their high current prices. A strategy to minimize this risk is to explore for relatively easily discovered deposits which can be put rapidly into production. Open pit deposits with simple metallurgy are therefore the main exploration target of most gold explorers. The lead time from discovery through feasibility to production has been less than five years in the case of FMC's Paradise Peak, Amax's Sleeper in Nevada, and the BP Cabaçal Deposit in Brazil, and is commonly under two years for small to medium size deposits in Nevada and Australia using off-the-shelf mining equipment.

Uranium has unique risks related to the sensitivity of the nuclear industry to social and environmental pressures which compound the normal commercial uncertainties of price based on supply and demand. At the present uranium price and with large deposits such as Jabiluka still unexploited, there is no commercial justification to explore for uranium. However, state-controlled nuclear agencies have an interest in funding exploration, in order to find ore deposits which may give them flexibility of supply. The logical strategy to minimize exploration risk under these circumstances, is to explore for reserves of cheaply developed, potentially low cost uranium, which may be brought rapidly into production in response to a price hike. *In situ* leach operations have very low capital costs compared to conventional mines and represent the ideal target for a policy-driven, electrical utility seeking a buffer against price rises.

FUTURE TRENDS

The present tendency of exploration companies to be driven by the immediate prospect of a commercial return on their investment, possibly by early realization of the value of their discoveries via stock market floatations, will continue at least for the short to medium term.

While the development of computer-based procedures for analysing and presenting geophysical and geochemical data will continue at its present fast rate, a desirable trend would be for geologists to return to careful high quality field work which ultimately can contribute more to reducing exploration risk than any number of computers.

Exploration in general is very light on rules, many of which are uncertain, but is heavy with information and data. Intelligent knowledge and information systems in future will provide the capability of testing the sensitivity of exploration to different theories and of applying a vast assemblage of information at the point of decision. It is unlikely that

TABLE 4.2. POLYMETALLIC PROJECTS IN ACTIVE STAGES OF FEASIBILITY OR DEVELOPMENT - 1976 (Modified from Mining Magazine, September 1976).

Project and Location	x Tons x 10 ⁶	Cu %	Pb %	Zn %	Au opt	Ag opt	Ore Contained Value (1987\$/t)
L. DUFAULT Quebec	3.0	3	-	3.5	0.03	0.8	119
CENTENNIAL Manitoba	1.27	2.1	-	2.6	0.04	0.75	99
GAYS RIVER Nova Scotia	10.5	-	3.0	6.0	-	-	99
MATTABI Ontario	5.9	0.8	0.7	6.9	-	2.8	133
STURGEON L. Ontario	2.1	3.0	1.5	0.6	-	6.1	141
LYON LAKE Ontario	3.6	1.2	0.6	6.7	0.01	3.6	149
CHIQUEMULA Guatemala	1.6	-	0.5	3.7	-	2.9	73
QUE RIVER Tasmania	3.0	0.4	7.0	12.5	0.1	5.3	288
WOODLAWN New South Wales	10	1.8	3.5	9.0	-	1.8	199
ELURA New South Wales	27	-	5.6	8.6	-	4.2	185
HILTON Queensland	45	-	6.6	6.0	-	4.7	165
NOAILHIAC-ST SALVY France	3	-	0.5	9.5	-	2.5	143
BODENNAC France	3	1.7	2.7	4.3	-	2.5	135

systems of this type will contribute significantly to reducing exploration risk in less than five years.

Mineral exploration will continue to develop as an engineering rather than a scientific discipline with an increasing demand on geologists to look beyond the field operation to the commercial return. Management will need to keep abreast of the new technical developments and scientific theory in order to remain competitive.

CONCLUSIONS

The probability of exploration success by the individual company is impossible to assess quantitatively with any confidence.

Risk may be reduced, however, by optimising each step in the program and in particular by:

1. avoiding elaborate theories of ore genesis and geology
2. maintaining the highest standards of field geology

3. measuring a wide range of geophysical parameters at low cost
4. recognition of characteristic ore-related associations by multi-element geochemistry
5. integration of geology, geochemistry, and geophysics
6. employing high calibre technical staff with a strong commercial orientation
7. constant funding over several years

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The opinions expressed in this paper are those of the author and are not necessarily shared by his employer, BP Minerals International, with whose permission it is published.

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TABLE 4.3. POLYMETALLIC PROJECTS IN ACTIVE STAGES OF FEASIBILITY OR DEVELOPMENT - 1987 (Mine Development Bimonthly, April 24, 1987).

Project and Location	x Tons x 10 ⁶	Cu %	Pb %	Zn %	Au opt	Ag opt	Ore Contained Value (\$/t)
HILTON Queensland	112.4	-	6.3	10.7	-	3.8	157
RED DOG Alaska	85	-	5	17.1	-	2.4	196
HELLYER Tasmania	16	0.3	7	13	0.06	4.6	218
IZOK LAKE Northwest Territories	10.0	2.9	1.5	14.4	-	2.19	194
LADY LORETTA Queensland	9.9	-	6.5	14.8	-	2.77	187
SCUDGLES Western Australia	12.1	1.1	0.6	9.3	0.044	2.36	139
WARD MOUNTAIN Nevada	17	1.5	1	4.5	-	2.5	86
GREENS CREEK Alaska	3.5	-	3.9	9.7	0.18	24	366
AL MASANE Saudi Arabia	8.3	1.5	-	5.7	0.035	1.28	95
THALANGA Queensland	4.4	3	3	9	-	2.9	162
IZAY CRUZ Peru	3.3	0.2	1.9	13	-	0.9	134
WINSTON LAKE Ontario	2.9	1.0	-	17.8	0.023	0.74	187
ISLE DIEU Quebec	2.3	1.2	-	22.4	-	2.77	236
BLUE MOON California	3.0	1.4	0.6	8.6	0.043	2.34	136
ANSIL Quebec	2.3	7.2	-	0.6	0.05	0.7	135
CERRO MAIMON Dominican Republic	3.5	4.0	-	1.9	0.01	1.18	91
MIDWAY British Columbia	1.2	-	7	9.6	-	11.96	213
RESTIGOUCHE New Brunswick	1.6	-	5.1	6.5	-	2.6	104
SARGIPALLI India	2.3	0.3	-	6.1	-	1.49	69
LALORI Papua New Guinea	0.4	4.0	-	1.6	0.093	0.24	129

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5. The Winston Lake, Ontario, Massive Sulphide Discovery — a Successful Result of an Integrated Exploration Program

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ABSTRACT

The Winston Lake volcanogenic massive sulphide deposit is located 145 km northeast of Thunder Bay, Ontario. It is hosted by Archean volcanic rocks of the Superior Province of the Canadian Shield.

Government maps portray a small volcanic belt comprising a lower sequence of "metasediments", a middle sequence of mafic volcanic rocks and an upper sequence of interbedded metavolcanic and metasedimentary rocks. A gabbro sill intrudes between the lower and middle sequences. The small Zenith Deposit was discovered outcropping within this gabbro sill in 1879. It was mined during the late 1960s.

In 1978, Corporation Falconbridge Copper (now Minnova Incorporated) completed reconnaissance geological and lithogeochemical surveys in the area. The lower "metasediments" were identified as

altered felsic volcanoclastic rocks (amphibolite facies).

In 1979 and 1980, detailed geological, lithogeochemical, and geophysical surveys were completed. The geophysical results were discouraging. However, the geological and lithogeochemical surveys discovered a locally sulphidic, cherty, bedded ash unit near the top of the calc-alkalic felsic volcanic rocks, and an underlying zone of intense hydrothermal alteration which was depleted in soda and enriched in zinc. The geological model developed, presumed the Zenith Deposit to be a xenolith of volcanogenic massive sulphide derived from a larger *in situ* deposit below the sill.

In 1981, eight holes were diamond drilled: four tested geophysical targets with negative results, the other four tested the geological model. The target was 125 to 250 m downdip of the cherty ash horizon. The results were encouraging. An exhalative horizon was intersected which yielded values up to



★ WINSTON LAKE DEPOSIT

0 100 200 300 km



Figure 5.1. Location map for the Winston Lake Deposit.

0.57 percent zinc over 4.3 m and disseminated copper mineralization averaged 1 percent copper over 7 m.

In May 1982, borehole pulse electromagnetic surveys (PEM) detected a strong edge-type anomaly with a conductor indicated downdip. Diamond drilling resumed, and the next hole, ZO-5, intersected 2.1 m of massive sulphides which returned values of 1.10 percent copper, 19.11 percent zinc, 22.2 g/t silver and 0.73 g/t gold. This zone is located at the base of the gabbro sill 300 m below surface.

The 3 100 000 t Winston Lake Deposit began production in January, 1968, the successful result of an integrated exploration program.

INTRODUCTION

The Winston Lake Deposit is located 145 km north-east of Thunder Bay, Ontario (Figure 5.1). The deposit is hosted by the Big Duck Lake volcanic sequence (Figure 5.2) within the Archaean Wawa Suprovince in the Superior Province of the Canadian Shield (Severin and Balint 1985).

Geological mapping by the Ontario Department of Mines in 1960 (Pye 1964) defined a westerly to northwesterly trending volcanic belt, the Big Duck Lake volcanic sequence (Figure 5.3), composed of three parts:

1. a lower sequence consisting mainly of "metasediments"

2. a middle sequence consisting of north and northeasterly facing pillowed mafic volcanic rocks
3. an upper sequence consisting of interbedded metavolcanic and metasedimentary rocks

A large lopolith-shaped gabbro sill intrudes the contact between the lower "metasediments" and the overlying mafic volcanic rocks. A small massive sphalerite occurrence, the Zenith Deposit, was discovered within this gabbro sill by surface prospecting in 1879. No significant work was done on the property until Zenith Metal Mines Limited was incorporated in 1952 to further explore and develop this deposit. The Zenith zinc deposit was mined during the late 1960s and produced 164 000 t of ore grading 16.5 percent zinc.

Corporation Falconbridge Copper (CFC), now Minnova Incorporated, was intrigued by the unique geological setting of the Zenith massive sulphide deposit. This paper documents the integrated exploration approach that resulted in the discovery of the Winston Lake volcanogenic massive sulphide deposit 800 m west of the Zenith Mine.

RECONNAISSANCE SURVEY

In October 1978, CFC completed reconnaissance geological and lithogeochemical surveys to assess the exploration potential of the Zenith mine area (Mactinen 1978; Severin 1979). Traverses were run at quarter mile intervals (Figure 5.3). The lower "metasediments" were identified as altered felsic volcanoclastic rocks (Photo 5.1) with a lithogeochemical signature (Figure 5.4) similar to that

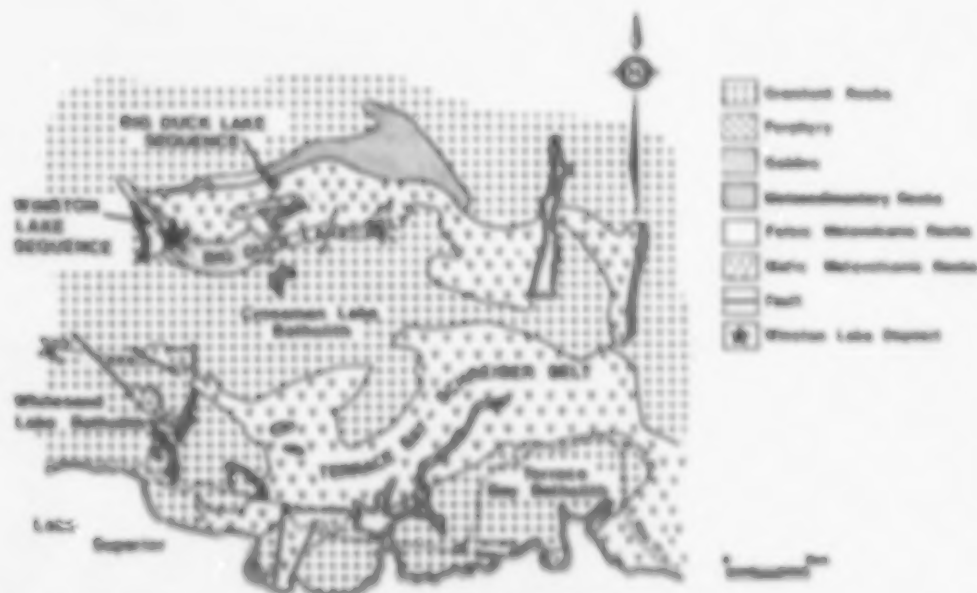


Figure 5.2. Regional geology of the area showing the Big Duck Lake volcanic sequence.

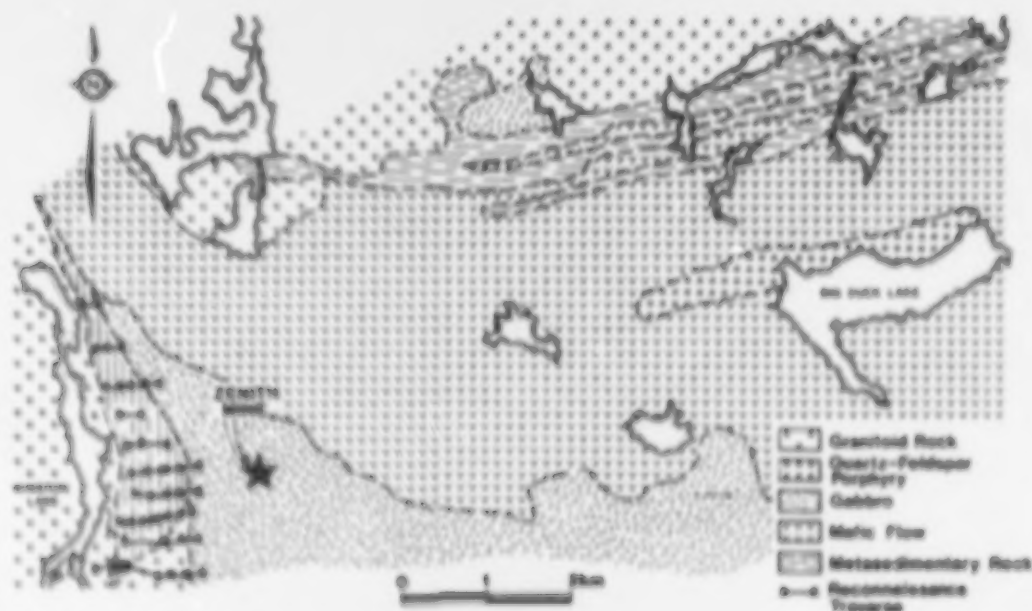


Figure 5.3. Big Duck Lake volcanic sequence (after ODM Map 2033).

recognized at CPC's Sturgeon Lake Mine where the ratio $Zn \text{ (ppm)} / (\%Na_2O \times 10)$ is helpful in delineating the fumarolic vent area. A discrete alteration pattern was defined by the ratios $Zn \text{ (ppm)} / (\%Na_2O \times 10)$ and $(\%K_2O / \%Na_2O) \times 10$ within the felsic volcanic rocks 1200 m west of the Zenith Deposit adjacent to the western contact of the gabbro. Forty-two claims were staked to the west and north of the old Zenith Mine and a joint option agreement was negotiated on the thirty-two claim Zenith Mine property.

DETAILED SURVEYS

In 1979 and 1980, detailed (1:5000) geological, lithogeochemical, magnetometer, VLF, and Maxim II surveys were completed. The geophysical results were disappointing, but the geological and lithogeochemical surveys discovered zones of cherty bedded ash (Photo 5.2) within the calc-alkalic felsic volcanic rocks and delineated the zone of hydrothermal alteration previously identified by the reconnaissance work (Pirie 1979; Unger 1980).

Detailed geological mapping defined the lower "metasediments" as a sequence of calc-alkalic (Figure 5.5, Jensen Plot) felsic volcanic flows and volcanoclastic rocks, and the overlying mafic rocks as a series of magnesium- to iron-rich massive and pillowed tholeiitic basalts. The contact between these two contrasting sequences is intruded by a composite sill-like gabbro. The Zenith zinc deposit occurs at a transition between gabbro and a metaprecambrian phase of the gabbro intrusion. Areas of cherty ash

occur at the top of the felsic volcanic rocks 1200 m west of the Zenith Deposit close to the gabbro contact. The volcanic rocks have been metamorphosed to amphibolite facies.

The effects of potential ore-forming hydrothermal processes on the felsic rocks are shown by well-defined zones of strong Na_2O depletion, FeO and MgO enrichment, and locally moderate to strong Zn enrichment. At the prevailing amphibolite metamorphic facies, this alteration results in a mineral assemblage of cordierite-anthophyllite $\pm$ garnet $\pm$ staurolite $\pm$ sillimanite. Riverin (1977) has shown that metamorphosed alteration pipes at Millenbach Mine, Noranda, Québec have cores of cordierite-anthophyllite. Regardless of initial rock type, a distinctive metasomatic trend develops across the alteration pipe showing depletion of calcium and sodium and enrichment in iron, magnesium, sulphur, copper, and zinc. Limited analyses of altered and unaltered Winston Lake felsic volcanic rocks plotted on an unfolded tetrahedron, indicate trends (Figure 5.6) similar to those described by Riverin (Severin 1980). Spatially adjacent fragmental textures in felsic volcanic rocks at Winston Lake support the interpretation that a fumarolic vent area might be defined by the zone of cordierite-anthophyllite alteration.

The geological map and lithogeochemical results are illustrated in Figures 5.7 and 5.8.

GEOLOGICAL MODEL

The fact that the Zenith zinc-rich massive sulphide deposit is hosted by gabbro is a geological anomaly.

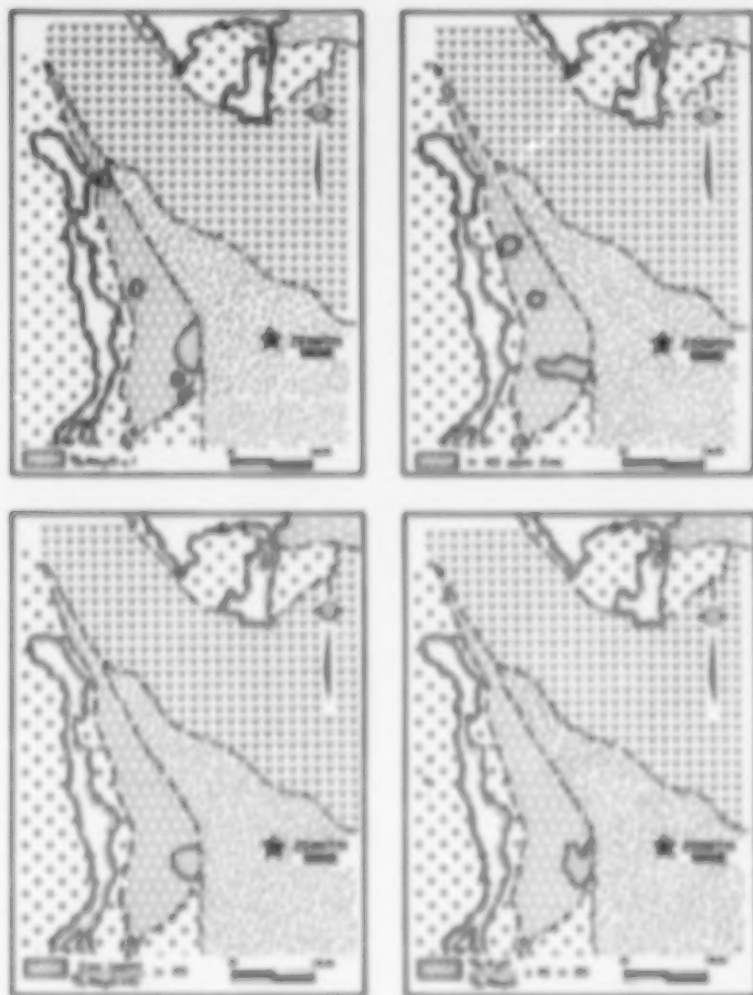


Figure 5.4. Remanent magnetic intensity results.

This gabbro sill intrudes the contact between underlying altered calc-alkalic felsic volcanic rocks and overlying unaltered tholeiitic pillowed mafic volcanic rocks. Genetic interpretations by previous workers (Tanton 1930, p.193; see account by Halet, p.42 in Pye 1964) suggested a vein-type epigenetic source or a magmatic zinc model to explain the Zenith Deposit. Corporation Falconbridge Copper's (now Minova Incorporated) work has clearly defined a number of features consistent with volcanogenic massive sulphide deposition. The geological model that was developed presumed that the Zenith Deposit was a large remnant of volcanogenic massive sulphide derived from a larger *in situ* deposit located at the top of the felsic volcanic pile. Assuming a simple dilation process by the gabbro, the schematic section shown as Figure 5.9 was proposed (Severin 1980).

DIAMOND DRILLING

In 1981, eight diamond-drill holes were completed. Four holes were drilled on property wholly owned by CFC. Three of these holes were drilled to investigate a pyritic horizon spatially related to the anthophyllite-cordierite zone within the felsic volcanic rocks. The fourth hole was drilled to test a weak Maxmin (I, VLF, and magnetic anomaly which occurs within the gabbro northwest of the Zenith Mine. The results of all four holes were disappointing. A second set of four holes were drilled to test the geological model. These holes were drilled on the adjacent Zenon Metal Mines property to explore the downward projection of the exposed cherty ash horizon, at a depth of 125 to 250 m. The horizon occurs at the top of the felsic volcanic package east of and

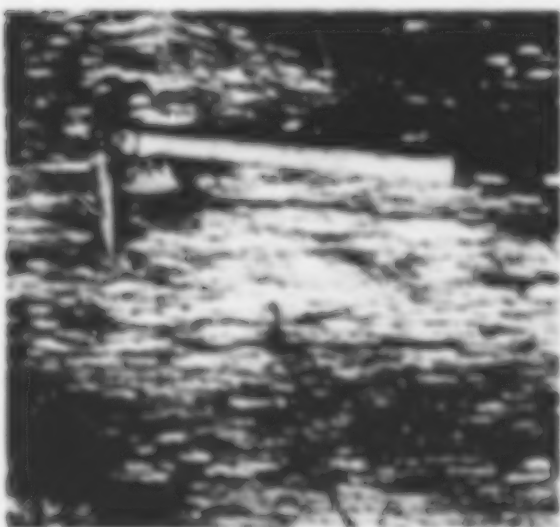


Photo 5.1. Altered felsic volcanoclastic rocks.



Photo 5.2. Cherty bedded volcanic rock.



Figure 5.5. Ternary plot for monovalent rocks and mafic igneous rocks.

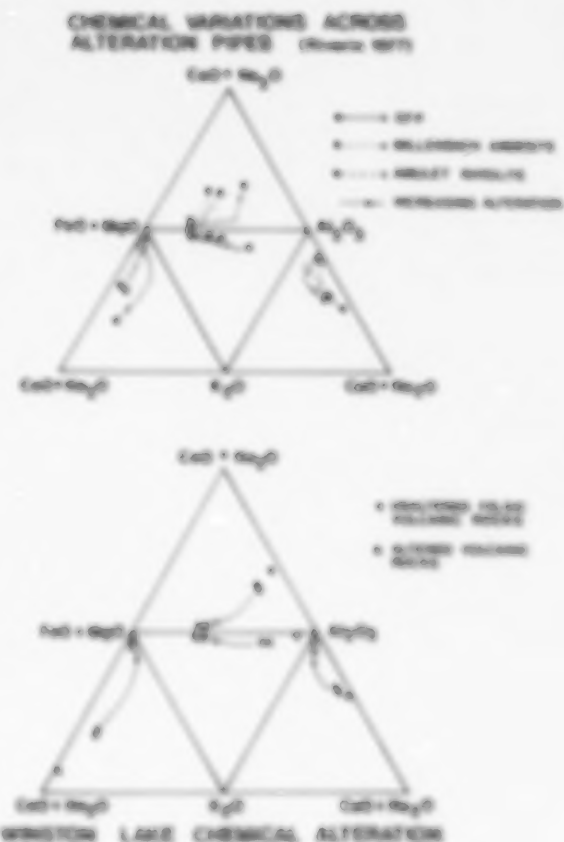
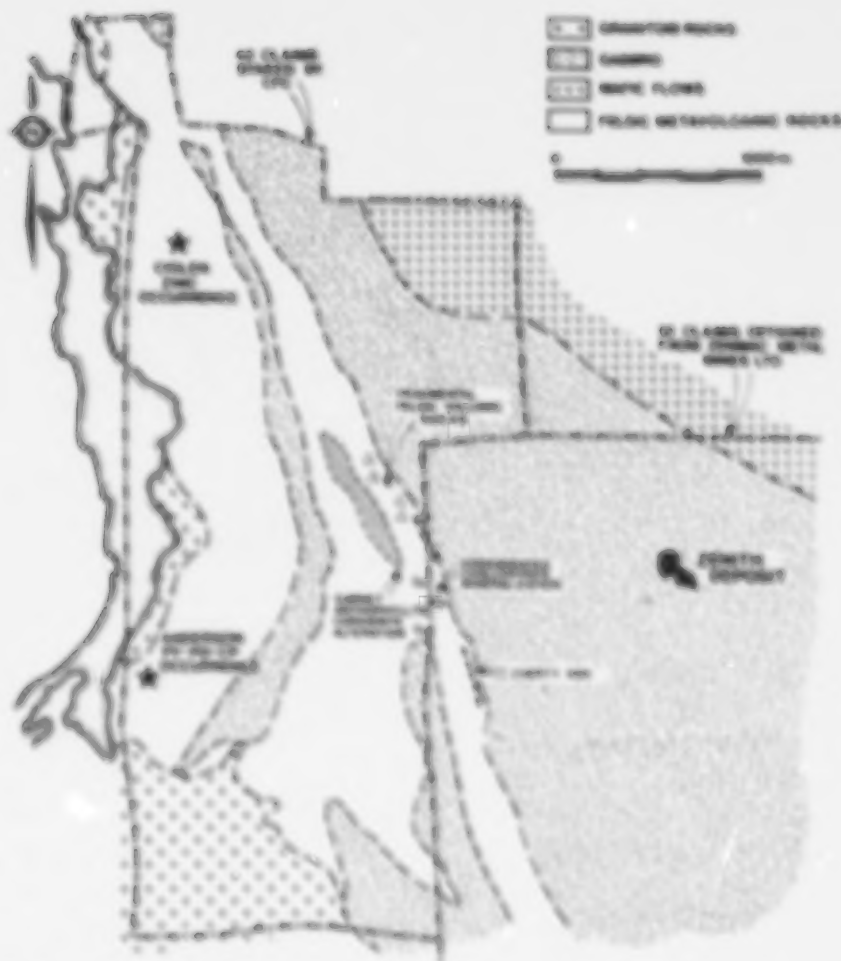


Figure 5.6. Unfolded rhyolite rocks.

Figure 2.9. Growth of *Chlamydomonas reinhardtii* on ^{14}C -labeled substrates.

The results were encouraging, an exhalation barrier was constructed by the holes and contained up to 0.17 percent zinc over 4.3 m.

BOREHOLE GEOPHYSICS

Directly pulse electromagnetic surveys (PEM), which had previously proven successful in analogous environments at CPC's Lac Dufault division in northeastern Québec, were completed in May 1982 and detected a strong edge-type anomaly (Figure 3.10). Directional PEM surveys indicated that a strong conductor was situated directly beneath the colline intersected by the 1981 diamond drilling (Baker 1982).

DISCOVERY

Drilling on June 2, 1962 to follow the PFM anomaly. On June 3rd of that day, drill hole ZO-5 intersected a 1.10 m zone containing 1.17 gppm, and 22.2 g/g silver, and the hole is located on the base of the gabbro at below surface.

The 1 100 000 t Winslow Lake Deposit (Figure 1.1) began production in January, 1988, the successful result of an integrated exploration program.

Table 3.1 summarizes the various phases of exploration activity.

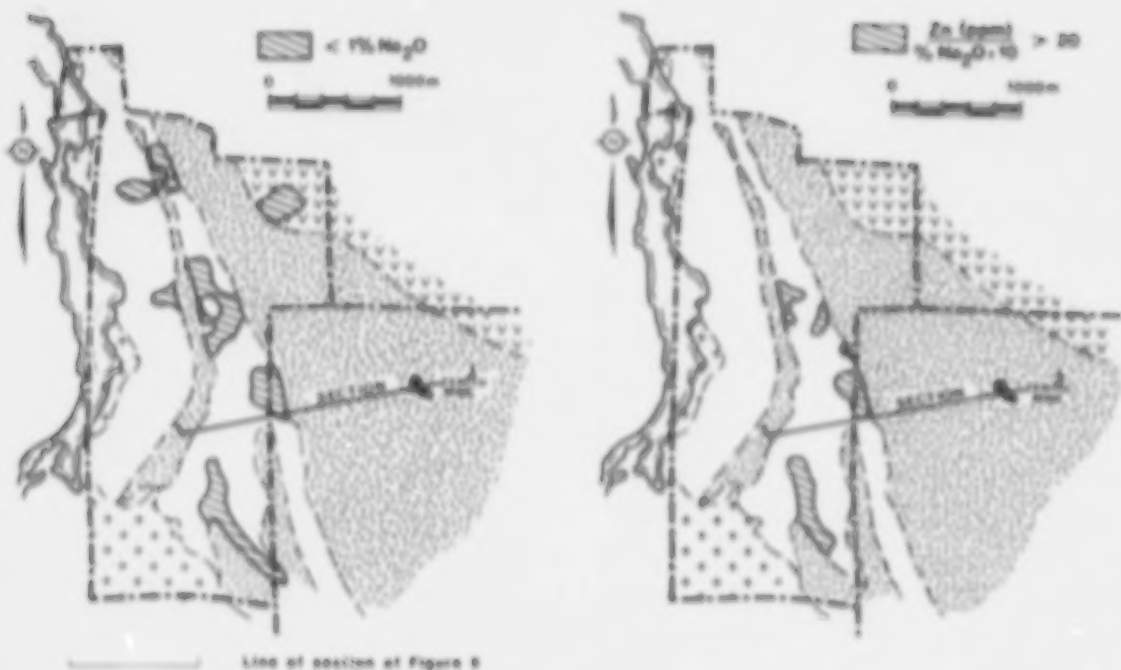


Figure 5.8. Detailed lithogeochemical results.

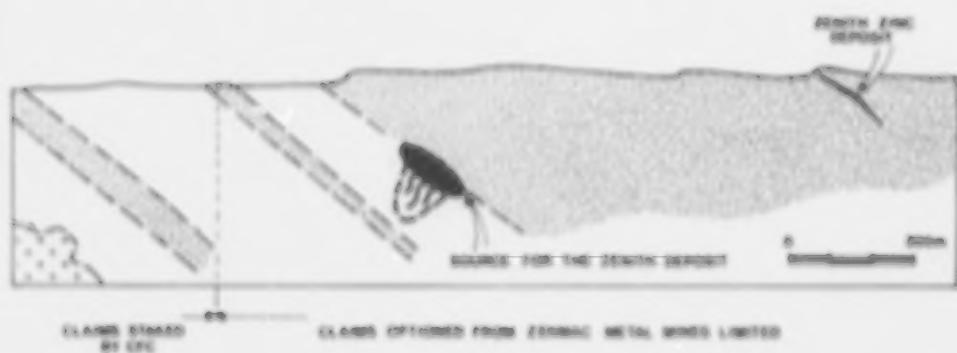


Figure 5.9. Schematic cross-section looking NW.

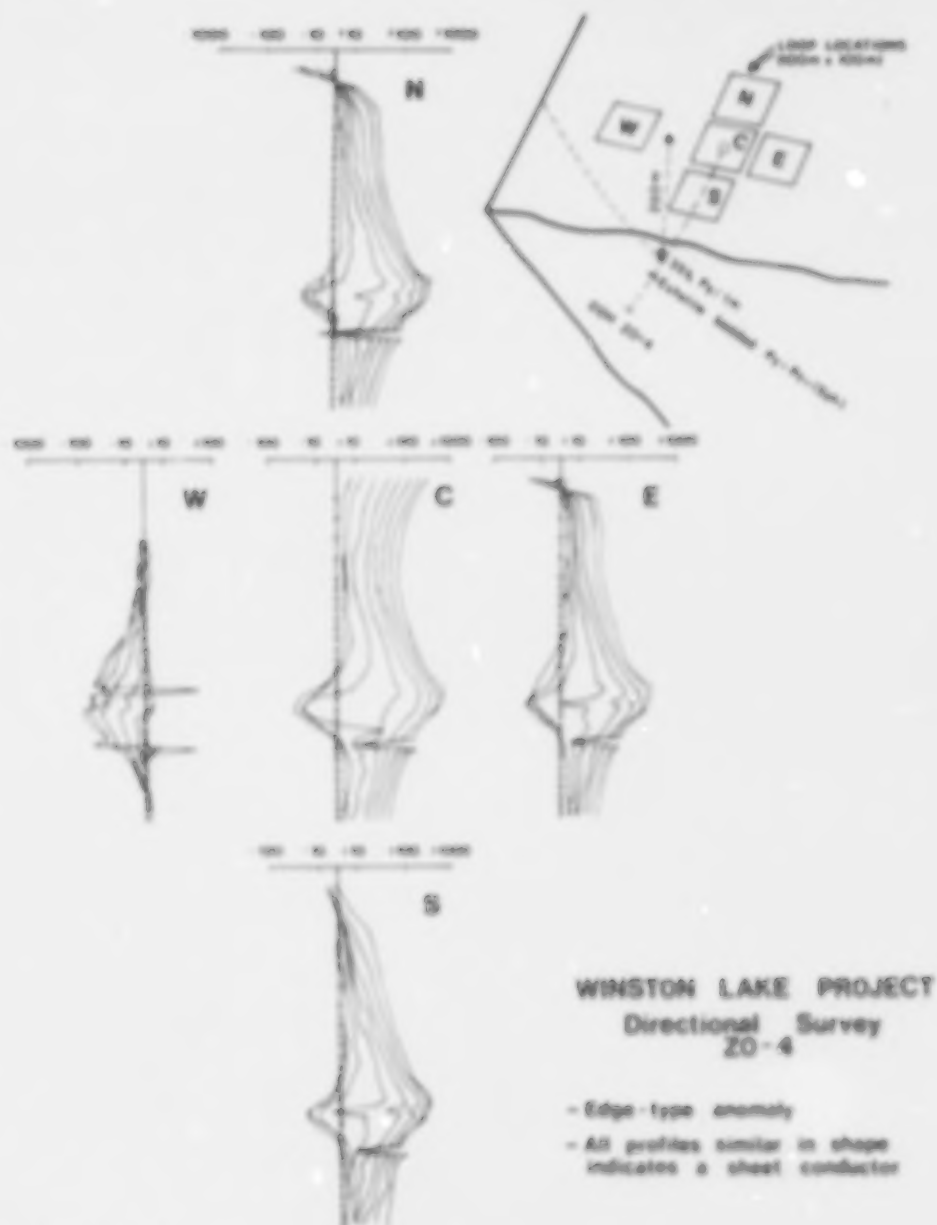


Figure 5.19. Borehole pulse EM survey.

EXPLORATION '87 PROCEEDINGS
THE ROLE OF EXPLORATION IN RESOURCE DEVELOPMENT

TABLE 5.1. EXPLORATION HISTORY—WINSTON LAKE DEPOSIT.

DATE	ACTIVITY	RESULTS
April 1978	Literature review re: old Zenith zinc deposit.	Reconnaissance program recommended to look at "metasediments" in Zenith area. Are the "metasediments" actually metavolcanic rocks? Zenith deposit could be a smallish in large gabber sill.
October 1978	Reconnaissance field work	Confirmation of felsic volcanics and geochemically anomalous areas indicating hydrothermal alteration.
Feb. 1979	42 claims staked to cover volcanics.	Linecutting initiated.
March - Aug. 1979	Detailed ground surveys VLF Magnetic Selected HLEM Geology Lithogeochemistry	Geophysics disappointing. Definition of anthophyllite/cordierite alteration zone in felsic volcanic rocks. Recommendation to option adjoining Zenmac Property.
July 1980	32 claims Zenmac Property optioned.	Linecutting initiated.
Aug. - Sept. 1980	Detailed ground surveys VLF Magnetic HLEM Geology Lithogeochemistry	Geophysics disappointing. Work defined cherty ash at top of felsic rocks. Geological model and diamond drilling proposed.
May - June 1981	Limited detailed mapping. Cherty ash horizon covered with low powered DEEPEM	Detailed definition of stratigraphy. Geophysics disappointing.
Sept. - Nov. 1981	Diamond drilling 6 holes: 1826 m	Cherty Zn-rich exhalite and strong hostwall alteration intersected.
May - June 1982	Data Review - Drill Proposal - Borehole PEM 3 holes: 1000 m	Discovery of Winston Lake deposit with the first hole of the program.

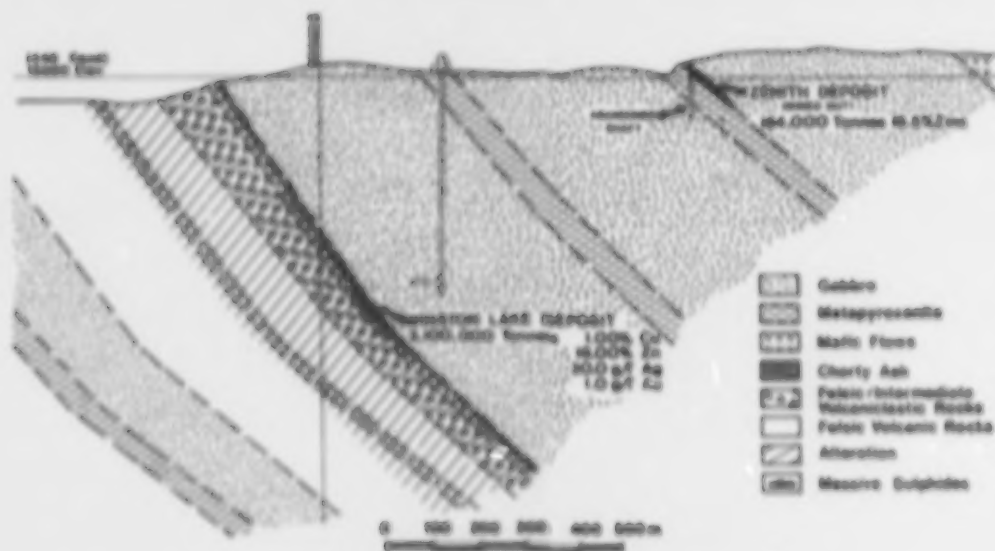


Figure 8.13. Cross-section of the Winston Lake Deposit.

ACKNOWLEDGMENT

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6. The Role of Mineral Exploration Towards 2000 AD

Keynote address at "Exploration 87"

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ABSTRACT

Exploration is to the minerals industry as research is to the pharmaceutical industry and much high-technology industries as computing, advanced materials, and microelectronics. Exploration replaces the ore deposit, which is the basis of production, and provides the means whereby new mineral products can be added to the production output. Ore deposits, like high-technology products, have a limited life and only through innovative research and development can their dependent industries survive.

Expenditure on mineral exploration will be a profitable research and development investment, if the result is timely, low-cost discoveries; especially if the discoveries are world-class deposits. We can maximize the chances of discoveries, and thus the return on investment in exploration, through innovative management. Decision making must be in the hands of competent, highly motivated scientists, and the confidence of those who provide the finance must be sustained. Success in mineral exploration requires technical excellence, persistence, flexibility, decentralized management, and stable financial backing.

The public image of the mineral explorer is not what it should be. Part of the problem is of our own making for we do not speak of our work in a language which is appealing and understood. Exploration is research and development, entrepreneurship, and exciting innovative experimentation, and discoveries are new inventions.

Successful mineral exploration, together with advances in mineral processing technology, renew mineral resources. Thus, mineral exploration needs and deserves the full support of our society.

OUR TARNISHED IMAGE

As we apply our skills in mineral exploration, skills which rely increasingly on advances in science and technology, we feel we are doing something very important and worthwhile. When explorationists meet at conferences such as this to share experiences, an air of excitement develops as we encourage each other, congratulate the successful explorers, discuss exciting new technologies, and describe new discov-

eries. But our image out in the community is not nearly so exciting and glamorous, nor is the importance of our discoveries understood.

What is our role in society, how do others see it and how will our role change as we approach the year 2000?

We are mineral explorers and we know what that involves. We know how important our work is to the prosperity of our countries, for mineral exploration is the first link in a chain of events which leads to mineral production and the generation of new wealth.

Mineral exploration begins with new ideas which increasingly have their origins in scientific research concerned with the source of minerals and metals in the Earth, how they migrate, and how and where they concentrate in the crust. Some explorers work at the frontier of fundamental research, while others are engaged in applied research in the field.

Successful mineral exploration is "going and looking", just as it was when the great gold discoveries were being made in Australia and North America in the last century. Now, however, we look with more than our eyes as we study the tectonics and lithology of the surface of the Earth, measure element abundance in a variety of materials, and use the most advanced technology to measure the physical properties of the near-surface and deeper crust. Moreover, we think before we go, studying the available pool of scientific knowledge, especially the geological, geochemical, and geophysical data bank to which scientists in industry, government research organizations, and universities contribute.

The factor most critical to success in mineral exploration is confidence; confidence which must be maintained while large sums of high-risk money are spent over long periods of time (Woodall 1984, p. 41-45). It requires people equipped mentally and physically to perform a difficult task.

Our ability to make the financial investment in mineral exploration an economic success depends on many factors:

- the extent to which we can reduce the search area cheaply, selecting the most prospective areas before expenditures per unit of area become large

- the effectiveness of the search technology we apply to the selected area

- the quality, skill, and motivation of the scientists and technicians entrusted with the search

- the strength of the web of confidence which links all involved, from the Board of Directors or financiers to the field crews (Woodall 1984, p.41-43)

However, mineral exploration is often the forgotten phase of the mining cycle. To the average citizen mining is digging holes in the ground, like shafts and open pits, and the creation of mills, smelters, and refineries, and even environmental pollution. Rarely do they think of exploration unless it be in terms of lone prospectors equipped with shovel, pick, and pan. People outside the mining industry would be astonished to see the sophisticated equipment on display at a conference like this, and more astonished still if they understood the sophistication of our data gathering and data processing and the skills required for the complex task of data interpretation. But the exploration phase is the most vital first phase of the mining cycle, for if exploration fails, there will be no mine. Moreover, if the explorer does not use resources and time efficiently, the total worth of discoveries will be less than the cost of discovery and there will be no new wealth generated to benefit either company or nation.

If we commissioned a public opinion poll to ascertain the community's perception of mineral explorers and the industry they support, I believe we would be disappointed by the result. The average citizen does not realize we contribute to their prosperity, and some believe mineral exploration and mining are no longer necessary in advanced nations. Moreover, few understand what resourceful and adventurous people mineral explorers are, or what a high level of science and technology they can apply. Nor is it generally appreciated that these committed scientists and technicians often sacrifice the comfort of the cities and the companionship of families for long periods in the service of their companies and their nation. Nor do many have a proper regard for those entrepreneurial people who provide the high-risk finance to support exploration. Then, when a discovery is made, some people believe we are taking from them something that is rightfully theirs, mineral resources which are the property and heritage of the people.

MINERAL EXPLORATION IS RESEARCH AND DEVELOPMENT

All know the manufacturing and service industries are important and that they are sustained by research and development (R&D). Everyone has heard about the high technology industries: the world of computers, space science, robotics, biotechnology, genetic engineering, communications research, material science, artificial intelligence, and so on. Few, however, have any concept of how their standard of living would suffer without our resource-based industries producing coal, oil, gold, copper,

lead, zinc, nickel, uranium, and so on, or that mineral exploration creates these resources through a vital R&D activity. Towards 2000 AD, our role will be to increasingly use all the skills of the research scientist to discover new mineral resources to replace those being used by society today, but it must also be to tell the people more about what we are doing in a language they can understand; in a language which has colour, enchantment, and correctly portrays the mineral explorer's contribution to their well being.

In popular language, mineral exploration is research and development. What is research and development, magic words symbolized by the letters R&D? It is financial investment in experiments, each one of which may cost millions of dollars and where there is a high risk that any particular experiment will fail. It is work designed to make an invention. It is systematic experimentation, the outcome of which is new knowledge, sometimes with specific practical applications such as new or improved products, processes, or services. Research and development activity only ceases after success is achieved, a discovery is made, and approval is given to build production facilities. Mineral exploration is just such R&D; systematic, costly experimentation with each drilling phase a new experiment aimed at making a discovery and creating new production.

A famous scientist said this about scientific research:

"Research is a calculated risk in which the odds are carefully assessed, the possible results considered against the amounts and the nature of the work involved, the equipment to be obtained and the space to be occupied. There are so many worthwhile projects. Always it is a question of priorities; we never lack ideas and we have to decide between them." (Weir 1969, p.66).

He could well have been speaking of mineral exploration.

Along with the popular words "research and development" goes the popular word "innovation". We are told that if we are to maintain our present standard of living we must be more innovative. Innovation is triggered by the imagination, and imagination is often triggered by experiments. Now imagination, experimentation, and innovation are not usually found in the ivory towers of corporate planners. Sixty percent of all innovation in Japanese manufacturing is said to originate on the factory floor. It is certainly so in mineral exploration. Innovation in mineral exploration originates most frequently in the minds of those active explorers who have firsthand knowledge of the search area and hands-on experience of the science and technology being applied. Their "laboratory bench" and "shop floor" is the field.

Another popular word is "entrepreneurship". We are told that we need much more of this magical elixir to rejuvenate our industries. The world of mineral exploration abounds with entrepreneurship.

TABLE 6.1: THE TWENTY FIVE BIGGEST U.S. CORPORATE R&D SPENDERS.

COMPANY	R&D AS PERCENT OF SALES
General Motors	3.8
IBM	6.0
AT&T	3.0
Ford	3.0
Du Pont	3.0
ITT	9.1
General Electric	3.0
Eastman Kodak	9.2
United Technologies	6.1
Digital Equipment	10.7
Hewlett-Packard	10.3
Exxon	0.0
Chrysler	2.0
Xerox	6.0
Dow Chemical	6.7
3M	6.5
Sperry	0.0
Johnson & Johnson	7.5
Monstanto	7.0
Monsanto	0.5
Honeywell	6.8
Lockheed	4.5
Marck	12.0
McDonnell Douglas	3.7
Boring	3.0

Source: *The Wall Street Journal*, November 10, 1986

Some mining companies are the most R&D intensive, the most innovative and entrepreneurial companies in the world. A useful yardstick to measure the intensity of R&D is the percentage of sales revenue that is re-invested in R&D. Some mining companies spend about ten percent of sales revenue on R&D if you include—as you must—expenditure on exploration. This, as a percentage of sales, is high by any standards and compares more than favourably with the 25 biggest U.S. corporate R&D spenders (Table 6.1).

The world of high technology has another popular word—"shelf life". Those involved, for example, in the production of new drugs talk about "shelf life" and know the "shelf life" of new drugs is often short. It is exactly the same in any high-tech manufacturing industry. To survive, such industries must be testing today the replacements for products currently on the store shelves; designing today the replacements for the products they are currently testing, and conducting strategic research to generate ideas for new products, the exact nature of which have yet to be defined. It is no different in the minerals industry. The "shelf life" of the manufacturer is the "mine life" of the deposit; product testing is ore deposit evaluation; product design is mineral exploration. Those mining companies most likely to survive will thus be those involved in the whole chain of activities from strategic exploration research

which develops ideas, through to applied research which tests those ideas in the field; activities which are encouraged and sustained by innovation and entrepreneurship.

Another popular word which is relevant to our role as mineral explorers is "renewable resources". The agricultural and forestry industries rely on resources which are renewable if responsible management is practised. In the case of the forestry industry we accept that it may take 100 years to replace a mature tree. The minerals industry is, however, often condemned for exploiting "non-renewable" resources. We should challenge this concept. There has been no decline in the ratio of metal consumption to metal in reserves, nor has the cost of metals increased in real terms. Advances in exploration science and technology, and advances in mineral processing more than replace the resources consumed. It is ignorance of the enormous extent of the mineralized Earth and the ingenuity of scientists and engineers that creates this myopic view of mineral resources as "non-renewable".

"Invention" is another popular word which means "discovery". Now, the golden rule of fair dealing in our society is that an invention belongs to the inventor. Thus, as the discovery of a mineral deposit becomes more and more the result of innovative research, that discovery becomes an invention and it is not true to say, and legislate as if, new mineral discoveries "belong to the people". They belong to the discoverer—the inventor.

Towards 2000 AD, as the known mineral deposits become exhausted, nations will rely more and more on production from deposits created by the ideas, the R&D, the experiments, the innovation, and entrepreneurship of the successful mineral exploration scientists. We must speak of our work using these words and we must strive to be seen not just as explorers but as inventors. The more difficult and expensive the search becomes, the more science and technology that is required for success, the more the explorers will believe they have created the mineral resources they discover. Their ownership rights over a discovery should be as valid as those of the inventor who patents a new miracle drug or microchip.

High-technology R&D in the manufacturing industries is vital to the well-being of any developed nation and for countries such as Canada and Australia, so too is the R&D we call mineral exploration. We must focus our limited research and development resources on "niches" where we have natural advantage. In Australia and Canada we are at a disadvantage in manufacturing because of our limited domestic markets in which to nurture new products, but in mineral resource R&D we have the advantage of large areas of land over which to explore.

As we approach the year 2000 AD it is vital people understand our role as being concerned with research and development. Only then will our public

image change. But men and women, and the politicians they elect, will not understand and they cannot be expected to understand what it is we do, unless they are told in a language which they can understand. It is not up to the people to learn our language, it is up to us to learn the people's language, using words they already understand and find exciting, like research and development, experimentation, innovation, entrepreneurship, and invention.

In our democratic societies in which the majority of our politicians are elected by those who live in the large cities, the minerals industry commands little political influence. We can only win the support of the majority through good communication and simple, logical, argument as we engage in a battle for the minds of the people.

Proper communication is becoming increasingly important within the corporate structure itself. As corporate management becomes more complex, more legal, financial, and taxation experts are needed on company boards to adequately protect shareholders' interests and to deal with increasingly complex government legislation and regulations. It is vital that these non-technical people be given every opportunity to understand what mineral exploration is and how it is changing. This can only be achieved by the mineral explorers themselves devoting time for discussion and explanation in language devoid of technical jargon.

If we are to be true to our role towards the year 2000 AD; if we are to maximize our success as inventors, we will need to master the use of the whole spectrum of science and technology. Moreover, as we approach 2000 AD we must become more skilled at describing to others what our true role has become.

MANAGING INNOVATION AND ENTREPRENEURSHIP

Effective inventors must have a vision of the undiscovered and a passion for discovery, for emotions awaken our faculties. We will be no greater than our desire.

Successful managers of exploration like successful managers of any R&D, must foster this spirit of adventure and experimentation.

The management of mineral exploration, which is the management of R&D, is the management of innovation. Innovation is triggered by experimentation, and the experiments of the mineral explorers are the search programs, especially the drilling programs, which are designed to test the new ideas. As Managers of R&D we must create a trusting environment in which experimentation is widespread (Hilman 1985, p.55-56).

Widespread experimentation means frequent failure and the managers of the R&D we call mineral exploration must be prepared to accept this. Never-

theless, widespread experimenting must not become an opportunity for everyone to do their own thing for as long as they like, in whatever way they please. The ideas to be tested must be clearly described, the experiments well designed, so that they throw light on the ideas being tested, and the results must be properly assessed (Hilman 1985, p.54-55). Managers must ask: what are we trying to learn, what results do we expect, what will success be, and what is the definition of failure? When success is not the result, managers must check the logic of the experiment and ask what new ideas have resulted and what the next experiment, if any, should be?

The management of mineral exploration, which is the management of R&D, is people management, for people innovate, people have ideas, imagination, vision, drive, and entrepreneurship—not organizations.

People only work well when they see real meaning in their work. We all need a higher goal than self interest, for profit alone is not an adequate long-term goal. There is that higher goal in the R&D we call mineral exploration. When it is successful it creates new towns, new industries, a wave of national prosperity, and years of extended prosperous mining and community life within established mining districts. The history of mining at Norseman in Western Australia is a simple but meaningful example of prosperity prolonged by wise managers supporting innovative mineral explorers over a long period of time (Woodall 1984).

Most of us are busy at this time searching for gold, and we need to believe this activity has value in a civilized world. The value of gold is subjective and is thus unlike food, clothing, shelter, or fuel. Nevertheless, it has been perceived throughout history to be a possession of superior quality. What John Maynard Keynes called 'this barbarous relic' still clings tenaciously to people's hearts. "It remains the only universally accepted medium of exchange, the ultimate currency by which one nation, whether capitalist or communist, settles its debts with another" (Green 1985, p.2). The rich give the poor goods and services in exchange for gold, and over centuries, it has protected the ordinary citizen from the excesses of Kings and politicians who can manipulate and debase each other's currency. To those who live in countries with unstable governments and banking systems it is the only acceptable store of wealth.

In the world of finance, gold is like a reservoir on a river in a region which suffers floods and drought. Like the reservoir, gold stores today's excess wealth for careful, thoughtful use tomorrow. But for gold to properly fulfil this role, the size of the world's store of gold needs to bear a meaningful relationship to the volume of world trade and wealth. There must be an adequate amount of gold in the world and that amount must increase with growth in trade.

Those who study the known ore deposits and their environments with care, and experiment with drills in the unknown, also help to unlock the mysteries of the origin of the Earth. How did it form? What stages has it passed through? What processes have been active in the past and how do they compare with those which are shaping the face of planet Earth today? Key parts of this record of processes and change are stored in mineral deposits which have formed throughout Earth history. This adds an entirely new and valuable dimension to the value of the work of those who seek to discover and study ore deposits.

We must aim to make our inventions, our discoveries, at the lowest possible cost. Here, governments must also encourage good management of resources by rewarding success, not expenditure. I note with apprehension the very large sums of money being made available to Canadian explorers through "flow-through share financing": i.e. by the Canadian government foregoing income from personal taxation to encourage exploration. I am concerned because this piece of government initiative encourages expenditure and rewards expenditure, not discovery. It is better for governments to forego corporate tax, as the Australian government does in the gold mining industry to encourage gold exploration. By so doing, they do not give the highest reward to those who spend the most money, but to those who are the most successful in making discov-

eries and creating new wealth through bringing those discoveries into production.

Mineral explorers are a unique group of experimenters, innovators, entrepreneurs, and inventors, whether they be in the field or laboratory. They are as vital today as they have been for generations. Our role has changed and will continue to change as we approach the year 2000 AD and science and technology become more vital to success. There is no question about the importance of our role, but we need to change the way we speak of that role to the community. Only then will our true role be seen, our image brightened, our work adequately supported by investors and government, and our successes and most skilful players recognized and acclaimed.

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Exploration in the Next Decade



7. Changes in Exploration: The Options Ahead

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ABSTRACT

Geophysical exploration continues to evolve rapidly, both in detail and in broad outline. Yesterday's dream of detecting and classifying electromagnetic drilling targets at depths of hundreds, rather than tens, of metres, is a reality even in Australia, where 15 years ago EM had never found an orebody. Development and use of many kinds of new technology has been assured through competition between companies, contractors, research organizations and individuals. This must continue: it is not an option. At the same time, opportunities in some areas are being lost by a general reluctance to properly evaluate other research products, for example in nuclear methods for logging.

Geophysicists have become successfully involved in several non-traditional applications, including geothermal exploration and development, gold exploration in a limited way, and coal exploration and mine planning. Involvement in other non-explora-

tion applications requiring the same expertise, especially the diverse problems of environmental protection, has been much slower to develop. The problems seem to arise in the 'cracks' at the boundaries between disciplines and between technologies. The oil industry practice of expecting individuals to operate as explorationists, regardless of their university labels, has been very slow to appear in the other industries. Yet this also seems to be an unavoidable option: exploration requires diversification; diversification needs academic input.

Future opportunities for explorationists to participate in development and extraction is an interesting possibility, especially as it is already an accepted fact in some industries. In other industries it is also an option, but one that must be pursued to help cope with swings in exploration activity.

Overall, it seems that the exploration community has some essential paths to follow, with very few real options if it is to survive.

8. Exploration Remote Sensing — A Look to the Future

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ABSTRACT

Remote sensing has changed radically over the last two decades. Before Landsat, most geologic remote sensing studies were purely photographic; the use of digital multispectral data was largely confined to topical research. Two largely concurrent events, the launch of Landsat in 1972 and improvements in the size, speed, and cost of computers, fundamentally changed remote sensing.

Empirical studies of landforms, structure, and lithology have been refocused by the introduction of processing techniques guided by physical property studies and are tied to an understanding of geological processes. As a further consequence, new instruments are being designed to collect detailed spectral data for mineral identification and detection of metal-stress in vegetation-covered areas.

Explorers face a bewildering array of options. Regional scale satellite data (MSS, AVHRR) can be processed at nominal cost to map limonite alteration and geologic structure. Higher resolution satellite data (TM, SPOT, SIR), with more specialized and costly processing, can be used to extend alteration mapping through detection of clay minerals and by resolving geomorphic detail. Aircraft data (multispectral reflectance/thermal systems and imaging spectrometers) with limited geographic coverage need highly complex processing to provide more specific mineral identification. Integration of remote sensing into exploration strategy will require extensive knowledge of weathering processes, and interpretation methods and costs.

INTRODUCTION

The field of remote sensing has changed radically over the last two decades, and, judging by current activities, will change even more dramatically in the future. Most remote sensing applications before the launch of the Landsat spacecraft involved photographic interpretations of aerial photographs. Use of digital multispectral data was largely confined to topical research studies by a small group of technical experts with access to main frame computer systems. Two largely concurrent events significantly changed the field. In 1972, the first Landsat satellite was launched to provide digital multispectral synoptic coverage of the Earth. During the 1970s, a computer revolution was also occurring. Astonishing improvements had begun in computer speed, size, and

cost. Small stand-alone mini- and micro-computers, first rivaled and later surpassed the earlier main frame systems. The field of remote sensing, largely as a consequence of these two events, has now joined the traditional methods of geophysics and geochemistry in mineral exploration.

LANDSAT MSS DECADE

Developments in the decade following the launch of Landsat began slowly. Conventional wisdom questioned the value of low resolution satellite data (80 m) compared to conventional aerial photography (10 to 25 m) and colour and colour-infrared photography had been used largely in an empirical sense to study landforms, structure, and lithology (Gregory 1974). The growth of digital image processing techniques, coupled with an increased understanding of the physical properties of geological materials gradually modified the interpretation process. Purely empirical reasoning based on subjective assessment evolved to greater reliance on scientific deduction (Owens and Rowan 1981; Watson and Ragan 1983; Watson 1987). Emphasis shifted to relating the ground reflectance observed by satellites and aircraft to the physical properties of materials, primarily spectral reflectance (see Hunt 1982) but including thermal, microwave, and spectral emission as well. Interpretation techniques began to be developed for enhancing and displaying diagnostic differences in these properties. New instruments, based on laboratory measurements and knowledge of atmospheric transmission windows, were also being devised and tested from aircraft to detect spectral features of a substantial number of minerals.

In the mid 1970s the primary application of remote sensing to mineral exploration was the use of the Landsat MSS (Multispectral Scanner) images to map limonite to infer structural zones and fracture domain boundaries (Gifford et al. 1977; Rainer 1978; Gold 1980) and to map limonite for detecting areas of hydrothermal alteration (Rowan et al. 1974). The colour-ratio compositing of MSS spectral bands to detect iron-oxide compounds, first employed in the Goldfield, Nevada, mining district, showed a substantial coincidence with alteration mapped in the field (Rowan et al. 1974). In another study classification, techniques were implemented using a known porphyry copper deposit to locate outcrops of hydrothermally altered and mineralized rock in Pakistan (Schmidt 1976). Limonite mapping and lineament studies were later integrated with

geochemical and geophysical surveys for exploration reconnaissance of porphyry copper in northern Mexico (Raines 1978), and for uranium deposit studies in the Powder River Basin, Wyoming (Raines *et al.* 1978).

The concept of multispectral band ratios was an important step in the development of remote sensing. The digital ratio, in addition to providing spectral information, reduces the effects of topography and albedo (brightness) in the scene. The interpreter, however, is required to deal with the physical properties of geological materials and aspects of the physics of radiative transfer in order to make an effective interpretation. It soon became recognized there were also significant limitations to the "limonite mapping" approach.

The MSS band ratios are very sensitive to the presence of vegetation and the moderately low resolution of the MSS system (30 m) causes ambiguities by averaging different spectral signatures — the mixed pixel problem. A more significant issue was the association of limonite with weathering and the need to detect other aspects of hydrothermal alteration such as the presence of clay minerals, sulphates and carbonates. Laboratory data (Hunt 1977, 1979; Hunt and Ashley 1979) and field data (Rowan *et al.* 1977) demonstrated that hydrous minerals display spectral absorption near 2.2 μm . A specially designed multispectral airborne scanner was flown over the Cuprite mining district, Nevada, south of Goldfield to demonstrate the feasibility of detecting the OH-absorption band near 2.2 μm of clay minerals and shales (Abrams *et al.* 1977).

MULTISPECTRAL AIRBORNE SURVEYS AND THE THEMATIC MAPPER

A new generation multispectral scanner called Thematic Mapper (TM) was devised for the Landsat satellite series with additional spectral channels near 1.6 and 2.2 μm and a thermal channel near 11 μm . Aircraft data were acquired to simulate this instrument and the Joint NASA/Oncon Test Case Project, involving many private companies, evaluated the utility of remote sensing technology for geologic mapping and exploration (Jettie 1984). Of particular interest to the mineral exploration community was a study of porphyry copper deposits in Arizona (Abrams *et al.* 1983). The results demonstrate the usefulness of additional spectral bands in the 2.2 μm region for identifying areas of hydrothermal alteration and mapping alteration zones. In a related study, the TM equivalent bands from a 14-channel multispectral scanner were raised to assess hydrothermal alteration in the Marysville mining area, Utah, (Podewski *et al.* 1983). In this study, some sulfates and monomuscovite-bearing alk-feld tuffs were distinguished from highly altered rocks using a band ratio image.

The TM scanner, launched on Landsat 4 in 1982, acquired on bands of spectral reflectance data with a resolution of 30 m and a thermal channel with a resolution of 120 m (see Figure 8.1). The substantial gains in morphological detail introduced by higher spatial resolution and the increased spectral information are illustrated by comparing TM with MSS data for the Goldfield area (Plate 8.1 see Colour Plate near end of volume). Arrows show two areas of alteration: Goldfield (upper) and Cuprite (lower). The limonite area near Goldfield that appears green on the MSS image in Plate 8.1 is yellow on the TM image due to the presence of limonite and of clay minerals with absorption in the 2.2 μm band. The area around Cuprite which lacks limonite is red on the TM image due to the presence of clay mineral absorption in band 7 (2.2 μm) that causes the band ratio 3/7 to be large.

Besides being used for mapping limonite and hydroxyl-bearing minerals, these data also have additional benefits in mineral exploration. Low spectral reflectance soils developed on contact metamorphic rocks that are present in aureoles around granitic plutons have been distinguished in TM images (Rowan *et al.* 1987a). The study, in the Encarnadura region of Spain, where silver, lead, zinc, and iron deposits are associated with contact aureoles of granitic plutons, concluded that these results may have important implications for mineral exploration in contact zones.

Because vegetation has pronounced spectral contrast (see Figure 8.1) in the region of reflected solar radiation (0.4–2.4 μm), a number of studies

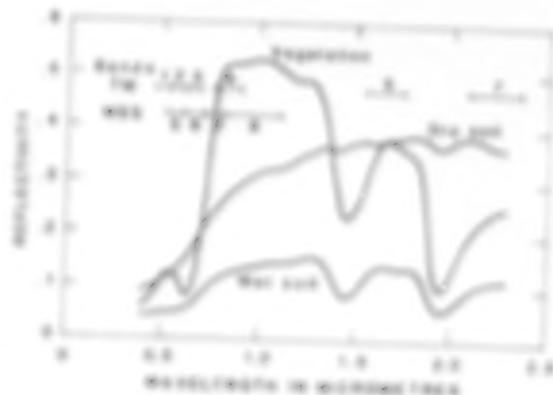


Figure 8.1. The spectral response of the MSS and TM satellite systems. Band 6 of TM, which is the thermal channel from 10.3 to 11.7 μm is not shown. Representative reflectance curves for vegetation and dry and wet soils are shown for comparison. The strong absorption features near 1.4 and 1.9 μm are due to water and, because the atmosphere is opaque in these regions sensitive channels are shown to avoid them. The red edge of the vegetation curve referred to in the text is the rapid rise in reflectance that occurs near 0.65 μm .

have focused on various aspects of vegetated terrain. An investigation using TM data in the New Almaden mercury district, California reported that geobotanical anomalies, faults, and fractures in the heavily vegetated Santa Cruz Mountains could be delineated along with regional lithology and structure of the sparsely vegetated Diablo Range (Lees *et al.* 1985). A technique to detect the presence of the characteristic vegetation spectral signature (Knepper and Raines 1985) can also be used to replace those pixels in the colour-ratio composite with a single band value. This deletes many spectral ambiguities from the colour ratio composite image allowing the observer to focus on spectral differences of rocks and soils (Knepper, Research Geologist, U.S. Geological Survey, Denver, personal communication, 1988). Another somewhat different approach uses principal component analysis of two band ratios to reduce the appearance of vegetation on the image (Fraser and Green 1987). Moderate to heavy vegetation cover obscures the spectral signature of rocks and soils. Extensive efforts (reviewed in Goetz *et al.* 1983) have focused on using spectral measurements to detect metal stress and to identify plant species and communities associated with lithology and mineralization.

HIGH SPECTRAL RESOLUTION DATA

During development of the TM system, the need for additional spectral channels was recognized to improve mineral identification. An experimental non-imaging 10-channel radiometer (five channels in the 2–2.4 μm region) with a ground resolution of 100 m was employed on a space shuttle in 1982. Diagnostic absorption bands for Fe^- , OH^- and CO_3^- bearing minerals were detected (Goetz *et al.* 1982; Rowan *et al.* 1983; Rowan *et al.* 1987b). A 500 channel airborne radiometer was also developed for aircraft and helicopter surveys (Collins *et al.* 1983) and a simple hand-held ten band radiometer designed for field surveys (Whitney *et al.* 1983). The 2–2.4 μm region is particularly important for remote sensing. It contains diagnostic spectral features in the Earth's atmospheric windows for phyllosilicate minerals, such as clays and micas, hydrated sulphates such as alunite, and carbonate minerals (Figure 8.2).

A significant discovery was the observed shift in the rapid rise on reflection at 0.65 μm (see Figure 8.1), the red edge, observed in vegetation affected by metal stress (Collins *et al.* 1983). The observed shift, about 10 nm (roughly one tenth the width of the corresponding MSS band) may be sensitive to heavy-metal concentrations as low as 50 to 100 ppm. Detection was demonstrated in two areas of sulphide mineralization under coniferous forests (Collins *et al.* 1983) and at a hydrothermally altered monadnock in a deciduous forest (Milton *et al.* 1983). However, a recent review of aspects of plant stress (Westman and Price 1987) suggested that ad-

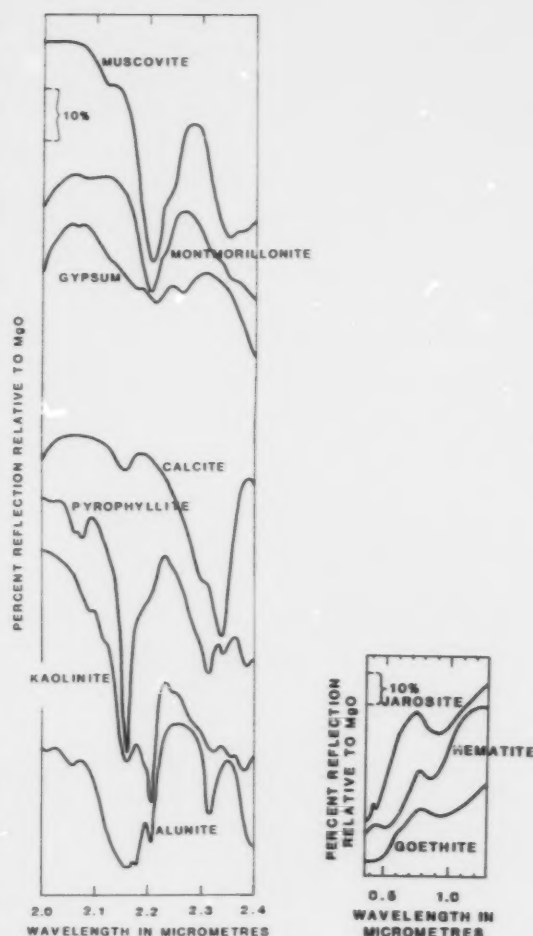


Figure 8.2. Reflectance curves of a number of minerals that display features in the 2.2 and 1 μm regions of the spectrum. The curves are displaced vertically for clarity. Clay minerals containing aluminum have absorption near 2.2 μm due to a combination tone. Calcite has a feature near 2.35 μm due to the carbonate group and the features between 2.2 and 2.3 μm for gypsum are caused by bound water (Hunt 1979). Alunite, a hydrous sulfate generally associated with hydrothermal alteration has a diagnostic spectral feature in the 2.2 μm region. Note that the broad response of the TM band 7 will detect the presence of absorption in this spectral region but is unable to differentiate between these phyllosilicate and carbonate minerals. The spectral response of the primary iron-bearing minerals in the 1 μm region are also shown. High spectral resolution is required to differentiate among them (jarosite, a hydrous sulphate can also be diagnosed in the 2.2 μm region due to a hydroxyl feature). Limonite, a combination of hematite and goethite, can be detected in MSS and TM data using appropriate band ratios to sense the sharp reflectance fall off at shorter wavelengths that accounts for the red color observed in the field.

ditional factors may also contribute to these spectral changes.

NASA then developed an experimental airborne imaging spectrometer (AIS) and flew it over several test sites (Vane *et al.* 1983). The instrument employed a two-dimensional detector array in order to image the ground simultaneously in 128 wavelength intervals from 1.2 to 2.4 μm thus making identification of narrow absorption features and individual minerals possible. A study of the northern Grapevine Mountains of California and Nevada demonstrates its potential for mineral exploration. Limestone and dolomite roof pendants and sericite-illite and other clay minerals were mapped (Plate 8.2, see Colour Folio) and verified in the field in a quartz monzonite stock (Kruse *et al.* 1986). At the Cuprite Mining District, Nevada, kaolinite, alunite, and buddingtonite, were detected (Goetz and Srivastava 1985) and preliminary results from a number of concurrent studies have tentatively identified minerals that are characteristic of alteration zones (Vane and Goetz 1985; 1986) and sedimentary basin environments (Lang *et al.* 1987). An advanced version of the spectrometer (AVIRIS) with 224 channels from 0.4 to 2.5 μm has just been test flown and will be collecting data over a number of research test areas. General availability of these type of data in the future is difficult to predict, although ambitious plans exist to acquire imaging spectrometer data from satellite as part of the Earth Observation System (Arvidson *et al.* 1985). The interpretation and display of these data, although in their infancy, are evolving rapidly.

A number of laboratory and field studies show considerable potential for mineral exploration now that high spectral resolution data are obtainable from air and will possibly be acquired from space by the middle of the next decade. Jarosite, an iron sulphate mineral that together with alunite is a positive indicator of alteration, can be distinguished from hematite and goethite (Hunt and Ashley 1979), which are ambiguous about alteration. A spectral shift that accompanies aluminum substitution into hematite was found to be diagnostic of unaltered areas (Buckingham and Sommer 1983). Samples of massive sulphide gossans and ironstones, confused with gossans, exhibit spectral differences in three different weathering environments (Raines *et al.* 1985). Ammonium minerals, detected at several mineralized hot springs and disseminated gold deposits, have diagnostic spectral bands in the near-infrared (Krohn and Altaner 1987). From measurements of samples from carbonatite-alkalic igneous rock complexes, it was proposed that the distinctive spectral characteristics of carbonatite material (carbonate, ferric and ferrous iron features, and, in some cases, rare earth element absorption bands) in conjunction with spatial context could detect rare-earth deposits (Rowan *et al.* 1986). Spectral changes in chlorite associated with variations in the ironmagnesium con-

tent could be useful for detecting alteration halos surrounding volcanogenic massive sulphide deposits (McLeod *et al.* 1987). Airborne spectrometer systems can now acquire the spectral resolution required by these laboratory/field studies. Current studies emphasize the significance of low temperature weathering processes and the need for better understanding of their spectral properties.

OTHER SATELLITE SYSTEMS

In addition to the more familiar satellite data from the Landsat system (MSS, TM), a number of satellites have obtained data of benefit in mineral exploration. One of the primary values of satellite data is repetitive synoptic coverage of the globe. The NOAA-AVHRR system provides reflectance and emittance data at 1 km resolution, with a nominal swath width of 2700 km, for synoptic scale overview. Spectral data in two reflection and two emission bands can be used to map spectral reflectance and spectral emittance of the ground. Thermal data from the odd-numbered satellites acquire data roughly two hours after local solar noon and midnight for mapping thermal inertia. These data are useful for detecting structures and differentiating regional lithologies (Honey and Tapley 1984; Watson and Hummer-Miller, in press). Plate 8.3 (see Colour Folio) is a colour composite image of spectral reflectance, spectral emittance, and thermal inertia data of the Arabian Peninsula.

A French commercial satellite, SPOT, launched in 1986 to obtain 20 m multispectral reflectance data (comparable to bands 2,3,4 of TM (see Figure 8.1) has a novel capability for 10 m resolution panchromatic stereo pairs. The latter will be useful for photogeologic structural analysis, lithologic and geomorphic analysis and logistics and support planning. An experimental thermal satellite system (HCMM) collected low resolution (500 m), night thermal and day thermal and reflectance data over a two-year period (1978-80) with limited coverage (primarily the U.S., parts of Canada, Europe, N. Africa, and eastern Australia). Several studies illustrate the potential use of these data for detecting structures, mapping outcrop patterns, and differentiating lithologies (Watson 1982; Watson *et al.* 1981, 1984; Watson and Hummer-Miller, in press; Kahle *et al.* 1981; Abrams *et al.* 1984).

Several radar satellite experiments including SEASAT, in 1978, provided a useful demonstration of space images for land studies (Elachi 1980) and of satellite radar data merged with Landsat MSS images for additional textural detail (Blom and Daily 1982). Two shuttle radar experiments (SIR-A, SIR-B) have shown the advantages of improved resolution and bandwidth and variable incidence angles for studying geomorphic aspects of terrain. Photogeological techniques have been used to map terrain categories, infer rock types, and deduce regional and local structures (Sabins 1983; Sabins *et*

al. 1980). Limited penetration in hyperarid terrain have also received considerable attention (McCauley *et al.* 1982). Empirical studies are being conducted for quantitative lithological discrimination using multiple wavelengths, polarizations and incidence angles (Daily *et al.* 1978; Blom *et al.* 1987). In some respects radar studies are thus comparable to the state of multispectral studies at the beginning of the Landsat era.

MULTISPECTRAL THERMAL STUDIES

The reflected solar region of the spectrum (0.4–2.5 μm) largely provides information from electronic transitions of iron compounds, and overtone and combination tones of hydroxyl minerals (clays, micas, and hydrous sulphates), and carbonates. The thermal infrared atmospheric window (8–14 μm) contains the fundamental vibrations of silicate minerals (Lyon 1965) but application is limited with the present instruments (Figure 8.3).

An experimental thermal infrared multispectral scanner (TIMS) was constructed (Kahle and Goetz 1983) and has recently been tested at a number of sites. If specialized processing techniques are used to enhance very subtle spectral differences (Gillespie *et al.* 1986), it is possible to identify silica-rich rocks and non-silicates (e.g. carbonates) and to distinguish between felsic and mafic volcanics (Kahle 1987). A study was conducted of the Carlin mine area, a disseminated gold deposit in northern Nevada, using the TIMS data (Plate 8.4, see Colour Folio). A distinct contrast can be seen associated

with outcrops of quartzite and quartz latite and of the disturbed area around the mine. In addition spectral anomalies can be observed on the image within a mapped jasperoid unit, in the spectrally neutral carbonate assemblage, and in adjacent surficial units (Watson *et al.* 1985). Multispectral thermal data will increase in use as additional and more narrow spectral bands can be provided. Satellite observations are somewhat constrained by the strong atmospheric absorption caused by ozone in the vicinity of the principal silica band. Aircraft surveys using active tunable laser systems have been shown to be feasible and being independent of thermal effects (Kahle *et al.* 1984; Eberhardt *et al.* 1987) have considerable potential.

Laboratory data (Lyon 1967; Hunt and Salisbury 1974, 1975, 1976) suggest that differentiation between the primary inorganic anions (carbonate, silicate, sulphate, etc.) and due to bonded metal differences may eventually be achievable in surveys. For example, the secondary spectral peaks for several carbonate minerals in the 8–14 μm atmospheric window (dolomite, calcite, siderite) are about a tenth of a micrometer apart and this resolution with appropriate signal to noise seems achievable in future systems. Spectral features of different minerals often overlap in both the reflected and emitted spectral regions, and it will also be useful to obtain supplementary spectral information to resolve ambiguities.

DATA ANALYSIS AND DISPLAY

The explosion in high spectral and spatial resolution data together with an increased emphasis on co-registering multiple data sets poses a major challenge to interpreters. Recent developments in analytical methods (Nagy and Swain 1987) indicates that expert systems will play an increasing role. Prior experience in the use of statistical classification schemes to distinguish rock units suggests that the link between remote sensing measurements and mapped geology is obscure. Artificial intelligence methods may be better suited for such well-defined problems as mineral identification and image and map co-registration.

The extraction of geological information from remote sensing radiance measurements is becoming highly complex. It requires detailed appraisal of weathering processes, atmospheric effects, detector response, and reflectance/emittance characteristics of terrain. We are on the threshold of employing analytical techniques (Clark and Roush 1984) that may ultimately lead to more precise identification and estimation of abundances of surface mineralogy. At the same time, we need to be aware that these highly analytical techniques may introduce more subtle forms of artifacts. Imprecise atmospheric and solar radiance models, estimation errors in grain size distribution, and system noise may produce false spectral features that result in misleading mineral

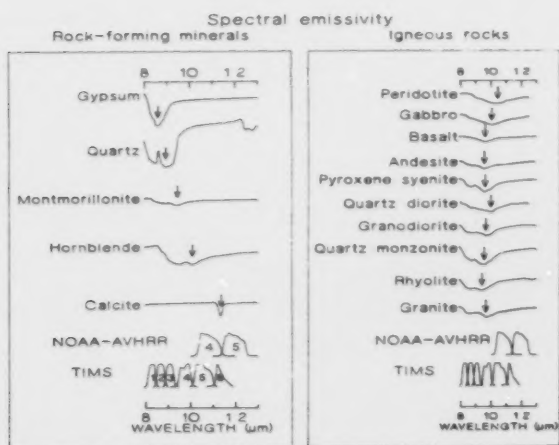


Figure 8.3. Laboratory spectral emissivity of selected rock-forming minerals and igneous rocks (Lyon and Patterson 1966; Vincent *et al.* 1975; Salisbury *et al.* 1987). The detector responses are shown for the NOAA-AVHRR satellite and the TIMS aircraft systems discussed in the text. Curves are offset for clarity and because of experimental limitations are primarily useful for indicating general spectral shapes and positions rather than absolute values.

identifications and abundances. The analysis will require considerable care in order to provide the increased understanding of geological processes at the Earth's surface that can guide exploration strategy.

A simple model can be used to illustrate how quantitative analysis may eventually be in remote sensing exploration. We begin by assuming that the exploration target is a mineral deposit that has been exposed to weathering by uplift and erosion. The transport of weathering away from the deposit can be approximated by a diffusion process (Figure 8.4). Initially, the detection radius (defined as the distance from the centre of the deposit to where the

surface mineral concentration equals the detection threshold) is small because the detectable minerals concentrate near the deposit. As time progresses these minerals diffuse outward due to physical transport and the detection radius expands. Eventually, the mineral concentration will fall, due to limited source material and outward diffusion, and the detection radius begins to collapse inward (Figure 8.4). Under some conditions, the detected area will become an annulus if geologic processes deplete the source materials. With appropriate estimates of rate constants and concentrations, it would be possible to establish target characteristics for particular geologic models. Planning future exploration surveys (resolution, detectors [spectral bands, band widths, sensitivity], processing, etc.) will require consideration of instrumental limitations and knowledge of weathering processes in addition to the constraints of the available geologic models.

CONCLUSIONS

Remote sensing studies have now demonstrated that the tools exist to develop a mineralogical-structural exploration strategy. Low cost regional synoptic data ranging from low resolution (1 km), wide swath (+2000 km) reflectance and thermal data (AVHRR), to higher resolution (80 m), 160 km swath multispectral reflectance data (MSS), are available for general reconnaissance and for mapping structures and limonite. Higher resolution/cost commercial satellite data are available for stereo mapping (SPOT-30 m) and for mapping hydrothermal alteration minerals (TM-30 m). Future satellite systems include the launch in the early 1990s of the Japanese Earth Resources Satellite system. There are plans for an optical sensor system (three visible/near-infrared bands, stereo, and four shortwave infrared bands) and a synthetic aperture radar system, both with a nominal resolution of 20 m and a 75 km swath). In the mid to later 1990s, the ambitious US Earth Observing System is scheduled to carry imaging spectrometers and multi-frequency radars.

Research aircraft with imaging spectrometers and multispectral thermal scanners have great potential for mineralogical/lithological mapping. Although the analysis of these data is only in its infancy, aspects of mineral abundance and association derived from the data should lead directly to the study of many geologic processes. However, because remote sensing data measure the properties of surficial materials, the detected mineralogic assemblages are those that result from near-surface weathering. Further research in weathering processes is vital for advancement of remote sensing.

The revolution, induced by detector technology and advances in computer processing, will require a fundamental re-thinking of how to apply remote sensing data most effectively in exploration. Future explorationists face a bewildering array of data types

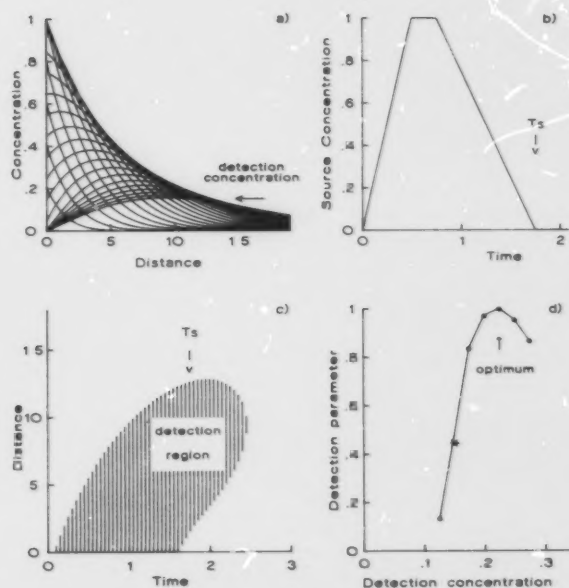


Figure 8.4. A simplified diffusion model of mineral concentration versus time and distance to illustrate aspects of remote sensing mineral detection. Figure 8.4a shows concentration versus distance curves for several times. Figure 8.4b shows one example of variation of concentration at the origin versus time (linear increase, a constant plateau, and a linear decrease). More complex forms are easily incorporated into the model; this example might represent uplift, exposure and removal by weathering. Figure 8.4c shows the variation of detection radius versus time for this particular model. Note that after $t=T_s$, when the deposit is removed, the radius increases, reaches a maximum, and then falls. Because there is both a minimum and a maximum detection radius, this case has an annular detection region. Figure 8.4d shows how a detection parameter (P) would vary with the detection concentration (C_d). The parameter (P) defined as the difference between two time integrals of the detection level: the first up to the system lifetime, the second after the system lifetime, is sensitive to the magnitude of the anomaly and the likelihood that the deposit has not been weathered away. For a given set of model and system detection parameters it would be possible to develop an optimum detection concentration and thus assist in devising the exploration strategy.

and sources. Regional scale Landsat MSS images at nominal cost, can be processed using conventional image processing methods and analyzed for regional structures, landforms, and areas of limonitic alteration. Topical scale imaging spectrometer data sets acquired from aircraft or satellite involving high acquisition costs, limited geographic coverage and requiring highly sophisticated processing and analysis. Many technological tools will be available, but it is their implementation that will provide the greatest challenge to future exploration strategy. This strategy can be guided by a geological model to identify remote sensing data acquisition and effective data display, constrained by economics.

Much of the research effort to date has focussed on areas with moderate to low vegetation cover. Although promising results have been achieved in the study of structure and plant stress for areas with heavy vegetation canopy, critical experimental tests remain to be done before we can determine optimum exploration methods.

Remote sensing is in many ways both a geophysical and a geochemical method. The remote detection of radiation from the ground's surface and the deduction of physical properties by analytical modeling methods is analogous to geophysical methods. The examination of surface alteration halos, trains, and fans is comparable to geochemical methods. Yet, remote sensing methods (with the singular but important exception of airborne radiometrics) do not directly sense buried deposits, as do geophysical methods, nor detect subtle low element concentrations as do geochemical methods. Instead, remote sensing methods can provide a spatially uniform data base containing information on surface mineralogy, structure, and weathering. That data base needs to be integrated with geophysical, geochemical, and field mapping results. The effective acquisition and interpretation will pose a major challenge to the field of exploration in the next decade.

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9. Looking Ahead in Satellite, Airborne and Ground Methods for Mineral Discovery

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ABSTRACT

During the next ten years, a wide range of new Earth Resource satellites will be placed in orbit by at least five countries. They will carry sophisticated radar and optical imaging systems that should prove immensely useful for exploration, particularly when integrated with new airborne and ground methods.

The new generation of airborne methods will include advanced digital time domain electromagnetic systems, multi-component magnetometers, airborne gravity, and airborne geochemical methods. Data acquisition for these systems will employ optical disk recording allowing high volume raw data to be permanently archived in minimum space for future reference.

Advances in ground methods will include the incorporation of low-cost and lightweight Global Positioning Satellite (GPS) receivers into geophysical and geochemical surveys of all types allowing rapid and accurate positioning of stations in three dimensions. This will greatly facilitate, for example, the routine use of the gravity meter as a cost effective exploration

tool. Highly miniaturized electronic equipment and large capacity low-cost digital memories will further increase the convenience of field portable geophysical instrumentation. New generation gallium arsenide circuitry will place very powerful super computers in low-cost small packages, allowing widespread access by geophysical companies to ultra-fast processing. Colour presentations of data will become routine.

New analytical developments such as the inductively coupled plasma/mass spectrometer will have a major impact on geochemistry. A better understanding of the geological and geochemical controls of mineralization will encourage the large-scale application of multi-element fingerprinting as a direct ore finding tool and as an assistance to mapping. Biogeochemical methods will also see increasing usage.

Fundamental geological/geochemical research will influence the exploration geologists thinking and lead to more effective identification of the correct areas for exploration.

10. Global Change: New Opportunities for the Earth Sciences

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ABSTRACT

World population is increasing by over 80 million per year and next century, the global population will reach ten billion. For all scientists concerned with resources, new priorities are appearing, new questions are being asked. The Report of the World Resource Institute issued in 1987 reflects changing concerns and focuses on topics such as: the environment and human health, tropical deforestation, the atmosphere and climate, soil degradation, biodiversity, and fresh water. At the same time, new concepts are appearing in the world of materials as detailed knowledge of structure and dynamics at the solid interface improve. Material scientists increasingly start with the question of need and then develop the material to meet it, atom by atom (as in the high vacuum growth of diamond).

Our fundamental understanding of Earth Dynamics is increasing dramatically with seismic tomography, crustal seismic studies, measurement of absolute plate motions, and global observations by satellites. If the concepts of plate tectonics accelerated the discovery of resources for materials and energy, the new observations will lead to even more profound developments.

In the future, resources and the related areas of research that will increasingly become priorities must include:

1. understanding total global fluxes of bio-essential elements
2. providing high quality materials for new fabrication technologies
3. materials for air and water purification
4. materials for construction and energy utilization
5. new materials for fertilizers and soil conservation
6. new materials and systems for waste disposal
7. new mineral and mining technologies to reduce environmental impacts

The new agenda is formidable and the new challenges assure an exciting future for the earth scientist.

INTRODUCTION

This year, (1987), the World Commission on Environment and Development, often called the Brundtland Report, was published. Its general message is clear: ultimately, we have only two resources,

people and the environment necessary to support them. One of the opening statements must be noted.

"In the middle of the 20th century, we saw our planet from space for the first time. Historians may eventually find that this vision had a greater impact on thought than did the Copernican revolution of the 16th century, which upset the human self-image by revealing that the Earth is not the centre of the universe. From space, we see a small and fragile ball dominated not by human activity and edifice, but by a pattern of clouds, oceans, greenery, and soils. Humanity's inability to fit its doings into that pattern is changing planetary systems, fundamentally. Many such changes are accompanied by life threatening hazards. This new reality, from which there is no escape, must be recognized and managed."

The statement requires careful consideration. We live in a demographically divided world, a situation which is fundamentally unstable. Because of our ability to observe on many scales, from fragments of atomic nuclei to planets, to observe all parts of the system from the solar radiation field to the roughness of the core-mantle boundary, we have become aware of our Earth System for the first time. We have become aware of the complex factors which influence the ultimate system.

SUN. LIVING CELL EARTH

Over little more than the past decade or two, we have been shocked by the rates of change in many parts of our life support system. We have been equally shocked to find that Western Man has made the largest changes to that system via his impressive technologies.

CURRENT RATES OF CHANGE

Man is now a major force in shaping the future of planet Earth. Man moves more mineral material than all natural processes. Man contributes to change in the atmosphere and waters. The human population is increasing at 86 million per year. All population projections show that, barring catastrophe on scales never seen before, population will move towards 10 billion next century. There is no need here to stress the gross inequalities of opportunity which influence the present population, except to note that, as this situation worsens and population expands, global stability, and our future, is under increasing threat.

Over the past two decades, there has been a growing concern that the man-induced and man-ac-

celerated changes will lead to changes with potential for catastrophic effects. Change is not new — it is part of all natural systems. What is new is the rate of change. For example, observations which are becoming increasingly more solid, show:

1. Polar ozone is falling at a rate far beyond the percent per year level.
2. Atmospheric carbon dioxide has changed from 310 parts per million in 1960 to 350 ppm now (13 percent).
3. Atmospheric methane, from a pre-industrial level of about 700 parts per billion, has more than doubled (at least 1 percent per year).
4. Atmospheric carbon monoxide has increased 20 percent in the past decade!

All current models predict that global temperature should rise, and that it should rise faster near the poles, where ice is stored. Current satellite measurements show that the solar energy coming into our planet is falling (Willsson *et al.* 1986). Global temperature is rising, sea level is rising, and now we have the first evidence that the Arctic is warming faster than the global average (4°C in the last 100 years, Lachenbruch and Marshall 1986). Man is changing the radiation budget of Planet Earth.

Wallace Broecker, of Columbia University, recently wrote (Nature 1987):

"We play Russian roulette with climate and no one knows what lies in the active chamber of the gun ... There is now clear evidence that changes in the Earth's climate may be sudden rather than gradual. Not only do our current managers lack a proper intellectual grasp of the problem, but they are obsessed with legislatively imposed 'five year reports', and give little attention to developing a long-term strategy to build the needed base of knowledge."

One could continue with lists of change, but here we mention only two more. According to Brown and Wolf (1984) we are losing topsoil globally at a rate of 0.7 percent per year. And, perhaps most disastrously of all, genetic diversity is being reduced at a rate of near 1 percent per year. Wolf (1987) provided the following information:

"One million species — out of a total of 5 million — are at risk of extinction by the end of this century."

The present rates of change cannot continue, or the future warmer planet will be bathed in ultraviolet radiation and will revert to being a habitat only for microorganisms, its only major life form for more than 3 billion years of its 4.5 billion year history.

THE NEED FOR NEW STRATEGIES

Modern science and technology is truly amazing. As a species, human-kind has passed from simple modifiers of materials to satisfying their needs at the atomic-molecular level, whether it be for a new antiviral agent or a new material for supersonic aircraft. At the heart of many of our great advances,

which have led to population explosion, lie the great chemical and energy industries.

But, in a balanced world, a stable world, where all the people have some chance of achieving their full human potential, our present systems must change. Our systems are failing now. Planet Earth will not tolerate for long the changes that are occurring. Imagine that all people had access to the energy-chemical facilities per person (for food, transport, construction, health, education, etc.) based on present western technologies. The perturbations mentioned above would increase by an order of magnitude next century. This is simply impossible. There is an urgent need to begin reshaping and modifying the living standards of all people.

The concerns voiced above have led to a dramatic new initiative, launched in 1986 by the International Council of Scientific Unions: the International Geosphere Biosphere Program — A Study of Global Change (IGBP). This program has as its theme: "To describe and understand the interactive physical, chemical, and biological processes that regulate the total Earth system, the unique environment that it provides for life, the changes that are occurring in this system, and the manner in which they are influenced by human actions," and its goal, "Thus, with an improved understanding of the system, a primary goal of the Programme is to advance our ability to predict change in the global environment. The development of this capability will require cooperative and complementary efforts with climate modellers in order to incorporate the appropriate level of understanding for relevant global biological, geological, and chemical processes into physical models of the earth system".

The dominant parts of this project include:

1. Understanding natural change, now and in the past; the parts played by the Sun and the Earth systems.
2. Understanding the couplings and interactions, between the biological and the physical systems.
3. Focusing on regions which are sensitive now (e.g. the Arctic, the Amazon Basin) and regions where population is changing fast. A dramatic example (but typical) of environmental and social degradation is shown by Haiti (*see* National Geographic, 172, Number 5, 1987).
4. The establishment of global observatories, using modern observational tools including satellites and where atmospheric scientists, biologists, soil scientists, and geologists will correlate their observations. There is a growing interest and commitment to this new initiative from many nations including U.S.A., U.S.S.R., India, Africa, China, Japan, Europe, the South Pacific, and Canada.

We are living in the centre of a tremendous natural experiment and man is at centre stage. At present, solar inputs are declining while sea level is

rising and global temperature is rising. Man is manipulating climate, and Western Man is providing the dominant forcing! Certain technologies have supported the growth of human population. These include our modern agricultural systems, health systems, energy systems, material and chemical systems, transport and communication systems, and the like. We must face the shocking conclusion that these systems may require extensive modification.

As Earth scientists, we play a vital role. We are the historians of the long term record of change. The new data on the climate record of the past 160 000 years from the Vostok ice cores of Antarctica is of dramatic significance (Jouzel *et al.* 1987; Barnola *et al.* 1987; Genthon *et al.* 1987). We understand the rates of natural processes better than scientists in any other discipline. We are also the providers of the raw materials needed for all great industrial systems. As data on the dynamics of planet Earth have improved, we have been very successful in providing such material as needed. If we are willing to accept the necessity of the need for technological change to produce sustainable systems, there are vast opportunities and exciting challenges in the fields of Earth Science.

THE EMERGING OPPORTUNITIES FOR EARTH SCIENCES

In approaching our new tasks, it is necessary that we consider new boundary conditions. These must include:

1. World population will rise to something near ten billion by the end of next century.
2. For a stable world, opportunity must have a degree of equality for all men.
3. New technologies must be developed to produce minimal environmental stress.

The basic Earth Sciences face new challenges. The IGBP demands that we quantify the past record of change. This involves the exact monitoring of the physical and biological systems of Earth, from the Sun down to the biosphere and from the Earth up to the biosphere. The mass-energy fluxes of the system, their changes, and short term fluctuations must be known. The high latitudes stand in a unique situation, for the polar regions will provide the early warning system of change.

The exact study of mass-energy fluxes which influence biological systems will provide increasing knowledge of the impact of climate fluctuations on life, and of the deeper systems, like groundwater fluxes and soils, which influence ecosystems and man. It is essential that we better understand climate better and its fluctuations. We must also understand the dynamics of clouds, ice, permafrost, and rainfall as never before.

In terms of the Earth resource base we face a number of fundamental new demands. Here I mention only a few examples:

1. We must look to new energy technologies with reduced environmental impact. Vast sources of energy in the hot or warm near-surface rocks would become available with adequate knowledge of rock mechanisms and global heat transport (Skinner 1976). Better devices for the production of nuclear fission and fusion energy are being developed (e.g. the Swedish Secure System of fission reactors developed by the ASEA corporation of Sweden). Solar energy devices will require new materials for large scale production of electricity. A fuel cycle based on the production of H_2 and O_2 from water (by solar or electric devices) would provide clean transport technologies. At the present time, Mercedes is testing H_2 -fueled, ceramic engine systems. The expansion of fuels using bio-fixation of carbon (ethanol as in Brazil or methanol) is a process that does not change the global CO_2 balance. Particular attention, however, must be given to new strategies to preserve soil.
2. The Earth Sciences must become more active in agriculture. Sustained production requires that the total chemical mass balance in soils be maintained. There must be an increased application of geotechnology to preventing soil erosion. The range of minerals in fertilizers must be improved to ensure that soil chemistry remains in balance. Mineral quality control in fertilizer production must be improved to eliminate some present problems such as cadmium in phosphates, a major problem in Europe.
3. Environmental quality control must be considered in the use of industrial minerals, for which there will be vast new demands as we move into an age of new materials, ceramics, glasses, etc.
4. There will be increasing demands for strategies of waste disposal and recycling technologies. While in recent years great attention has been focused on radioactive wastes, the general industrial waste problem presents yet greater problems. Improved knowledge of the sea-bed is needed to understand its potential for waste disposal.
5. One of the great problems facing man is that of storage of essential commodities to reduce the impact of natural fluctuations that will surely occur. Imagine a year "without a summer" when we have 10 billion people! As the world is covered with giant cities and crowded rural areas we must change our present methods to the far more secure systems of underground storage. Such systems must be developed for all essential commodities (water, gases, foods, fuels, etc.). Geotechnologists will be required as never before.

6. Earth scientists have become experts in the field of remote observation using robotic devices and are experts in analytical chemistry. Satellite and deep ocean devices will need to be developed and modified to monitor the state of soils, erosion, and the chemistry and biology of all important water systems.
7. The time may be fast approaching when we will learn to influence climate. It is here that our developing knowledge of climate and atmospheric gases, and of resources like fossil fuels will play a vital role. Could we prevent an ice age?

CONCLUSION

Finally, I would like to quote a statement from the International Institute for the Environment and Development and the World Resources Institute (1987), Sigma Xi (1987).

"We are witnessing the birth of a sweeping new science. From it will come a powerful new understanding of the planet's structure and metabolism that could vastly improve the chances of sustaining billions more people. It's subject is nothing less than the composition, behaviour, and interactions of the planet's nonliving realms or phases — the atmosphere, geosphere, and hydrosphere — and its living realm, the biosphere, which encompasses parts of each of the others."

Perhaps this statement summarizes it all. We face the choice of changing much of our technologies, or of living in a world of potential catastrophe. The choice was eloquently summarized by Thomas Malone, former Foreign Secretary of the U.S. Academy of Sciences (1986), "Can Science and Technology develop the knowledge base upon which the power of world opinion operating through governments can choose a path with attractive vistas instead of one that places in jeopardy so many of the values mankind treasures?"

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11. New Horizons in Mining Geophysics

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ABSTRACT

Rapid advances in electronics in general and computer technology in particular will make possible major improvements in the speed of computation, cost, power consumption, and physical size of geophysical instrumentation. These improvements will result in greatly increased data volumes, real time signal processing, and data handling capability for both airborne and ground surveys.

The digital field data will increasingly be processed, interpreted and presented, in a routine and cost-effective fashion, using powerful, but inexpensive, microcomputers and plotters. The trend will be, in many methods, to provide final presentations which portray the interpreted distribution of physical properties in the earth, rather than just corrected field data. In addition, image processing techniques will be more broadly applied by geologists to facilitate their interpretation, in geological terms, of the digital data.

Simultaneous, multi-parameter and multi-sensor surveys, under the control of portable microcomputers, may become as commonplace for ground geophysical surveys as they now are on airborne surveys. Self-consistent interpretation, by computer, of this plethora of field data, will permit the deduction of derived subsurface geologic sections with improved validity and greater meaning to the explorationist.

Borehole geophysics will come into more general use, both for certain types of at-hole measurements, and for remote detection. High-resolution, shallow seismic methods may be increasingly used for both surface and borehole exploration.

Optical detection methods, based on both solar reflectance spectra and on time-resolved, laser-induced fluorescence, will be used to map the distribution of many minerals of direct or indirect economic interest, at the earth's surface.

INTRODUCTION

Any technological development in mining geophysics is meaningful only if it will be accepted into general use by the exploration community. Acceptance will occur only if and when the development truly serves a need of the explorationist. Therefore, in order to determine which of the many opportunities for advancement in our science are really of practical significance, we must bear in mind the needs of the

explorationist, as they presently exist. We may list them as follows:

INCREASED EFFICIENCY IN THE GATHERING, PROCESSING, INTERPRETATION, AND PRESENTATION OF THE GEOPHYSICAL DATA

Regardless of how the social or economic systems vary from country to country, beneficial consequences will arise from increased efficiency in all stages of geophysical activity. Whether the cost of the geophysical exploration of a given area is measured in monetary terms or in labour (man-days), the reduction of that cost improves the probability of finding mines within the limits of one's budget and human resources.

IMPROVED SIGNAL-TO-NOISE RATIOS

If we can improve our ability to detect useful signals while suppressing unwanted noise, we may derive many benefits: a reduction in the time required for a given measurement accuracy, an increased depth of penetration, and/or a reduced power requirement (for controlled source measurements). In some cases, signal-to-noise improvements may permit a type of measurement to be made which might otherwise not have been feasible under the circumstances. Improvements in signal-to-noise ratios may also be used to increase the useful resolution (or "sensitivity") of geophysical methods.

IMPROVED RESOLUTION BETWEEN GEOLOGIC SOURCES

We would like to enhance our ability to resolve targets of choice from "geologic noise".

IMPROVED INTERPRETATION OF THE GEOPHYSICAL DATA IN TERMS OF THE SUBSURFACE GEOLOGY, AND INCREASE IN THE DIVERSITY OF MINERAL DEPOSITS OF ECONOMIC INTEREST WHICH ARE DETECTABLE BY GEOPHYSICAL MEANS

Whereas these may appear to be two needs, they are intrinsically interrelated. Despite the fact that we are currently able to detect many types of mineral deposits by existing geophysical means (e.g. iron, massive sulphides, porphyry coppers, diamond pipes, uranium, etc.), we are not nearly so successful in detecting certain other types of deposits of current or potential interest (e.g. precious metals, bauxite, molybdenum, tin, tungsten, rare earths, etc.).

In response to the above-mentioned needs, many facets of the science of mining geophysics are

advancing rapidly at the present time, based upon improvements in sensor technology, materials science, and above all, in electronics and computers. Let us examine some of these advances which, on the criterion of real need, are having or are likely to have a significant effect on the practice of mining geophysics.

THE IMPACT OF MICROPROCESSORS AND MICROCOMPUTERS

The remarkable spiral in the development of microprocessors, microcomputers and their peripheral devices, is having an enormous impact on all aspects of mining geophysics, including the instrumentation for data gathering, data processing, data interpretation and data presentation. We have really only begun to incorporate and exploit the possibilities afforded by these software-controlled devices. In addition, should the present pace of their development continue, we will not likely exhaust the possibilities afforded by each new generation of faster, more powerful, smaller, less expensive, and more power-efficient devices before it is followed by yet another new generation of devices which exhibits even superior performance.

DATA GATHERING AND RECORDING

It has been approximately two decades since the airborne survey sector started using on-board computers and peripheral devices for data gathering and recording in their operations. More recent advances in this field have served to open new possibilities: improved real time signal processing; distributed intelligence; reduced size, weight and cost of installation; and greater tolerance of environmental conditions.

For ground and borehole surveys, however, recent developments in CMOS (complementary metal oxide semiconductors) low power-consumption microprocessors, microcomputers, and peripherals, have brought about major changes in field instruments and surveying practice. In fact, we are now seeing a repetition, on the ground, of airborne survey's transition into the computer age.

Small, environmentally hardened, battery-operated, portable microcomputers may now control a multiplicity of sensors, process their data and record them in solid state memory. Photo 11.1 shows an example of such a system, wherein a dedicated microcomputer controls up to six sensors (two total magnetic field, one controlled source EM, two VLF magnetic field, and one VLF electric field) and receives, processes, and records up to 21 independent data streams. These multiple measurements may all be made on a single traverse by the operator over each survey line, in a highly cost-effective fashion.

Some of the potential benefits from these programmed-intelligence-based instruments may be il-



Photo 11.1. Microprocessor-based ground geophysical system operating magnetometer, VLF and electromagnetic sensors simultaneously.

lustrated by the newly developed gravity meter shown in Photo 11.2. This device is programmed to:

- digitally stack its readings for signal enhancement, while statistically rejecting erratics and indicating the standard deviation of the mean
- correct for errors in the instrument leveling
- correct for residual long-term instrumental drift
- correct for an inadequate temperature stabilization
- correct for tidal variations
- store all information in solid state memory

All of these functions are performed automatically upon a single keyboard command by the operator.

Intelligent signal processing, in real time, through software-based algorithms administered by the microprocessor, may provide improved signal/ambient noise enhancement. This ability may result either in a reduction of reading time (for a given desired accuracy of measurement), a reduction in transmitter power for primary signal generation in controlled-source methods, or in higher (meaningful) sensitivity of measurement.

The first wave of microprocessor innovation, employing 8 bit CMOS devices, has already overtaken most of our standard ground-geophysical in-



Photo 11.2. Microprocessor-based automatic gravimeter providing real time correction for tilt errors, tidal variations and drift.

strumentation. Much faster and more powerful 16 bit microprocessors and microcomputers, are already in use, and 32 bit devices are now being instituted. Their potential in regard to improving data quality, speed, and diversity of measurement, will be limited mainly by the imagination of the geophysicist and of the software programmers. Among other benefits, they will permit the digitization and digital signal processing of the full wave forms measured.

In ground surveys, the ability to expeditiously measure and record a multiplicity of independent geophysical parameters simultaneously, provides the means of obtaining a more faithful representation of the subsurface distribution of the physical properties of the earth. For example, from multi-frequency or multi-time transient electromagnetic or induced polarization (IP) measurements, one may deduce quantitative information about the conductivity and IP characteristics of the ground.

DATA PROCESSING, INTERPRETATION, AND PRESENTATION

With all types of geophysical data from airborne and ground surveys now available in digital form, we will shortly see the virtual elimination of manual handling of the data in all its aspects, including editing, correcting for various time or environmental factors,

positioning, processing, interpretation, and presentation. The absolute necessity for data handling by computer has long been evident for airborne surveying and is now proving its merits for ground geophysical data as well.

Figure 11.1 (after Johnson and Fujita 1985) presents a section of a contour plan of the resistivity of the earth obtained by computer interpretation of a helicopter-borne electromagnetic survey in Japan. Ground investigation and drilling of a higher conductivity zone so detected in this area led to the discovery of the extremely rich Hishikari gold mine. It is clear that this interpretation and presentation was made economically feasible only by the use of a computer and a suitable software program. It could hardly have been contemplated using manual interpretation methods.

Digital image processing by computer is gaining popularity as a means of significantly improving the structural interpretations that may be made from contour maps of geophysical data, in particular, aeromagnetic data (e.g. Kowalik and Glenn 1987). Image processing techniques employed to date include: presentation as small-scale grey-level images, local contrast enhancement, artificial ("sun angle") illumination, and directional filtering.

By such means, one may possibly reveal the presence of faults and folds not readily recognizable from the standard contour map of the data. In addition, if there is a series of strong features striking in one direction, by directional filtering and artificial illumination, we may selectively suppress the effects

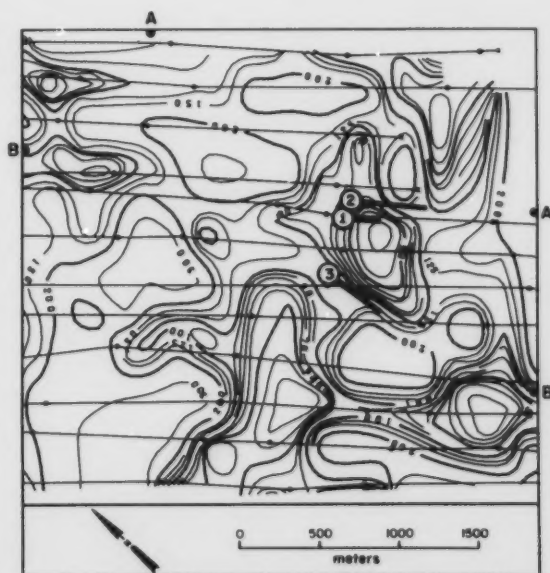


Figure 11.1. Hishikari Gold Mine, Japan; apparent resistivity contours derived from helicopter-borne electromagnetic survey, 735 Hz data (after Johnson and Fujita 1985).

of these features, thus allowing weaker structural and lithological features to show through.

Photos 11.3A and 11.3B show an example of the application of the artificial sun angle technique to aeromagnetic data in Ontario. Photo 11.3A is a monochrome plot of aeromagnetic data with a northeast sun illumination angle. It tends to highlight a north/south striking dike swarm as well as features that strike east/west. By changing the sun illumination direction to the north, as in Photo 11.3B, the effect of the dike swarm is greatly suppressed. In addition, the change of sun angle to the north allows the northeast-striking structures in the area to be much more clearly defined.

Similarly, equally significant interpretation programs may be routinely and cost-effectively applied to ground survey data, often using microcomputers which are suitable for either field or office use. For example, spectral IP parameters, usually the Cole-Cole parameters, designated M , τ and C , may be routinely extracted by microcomputer from the decay transient of time domain IP measurements, by curve matching to a large family of forward solutions. From the two parameters (τ and C) it may be possible to determine the size distribution of metallic particles in an area (Pelton *et al.* 1978). It has been found that the parameter τ increases almost as the square of the average grain size of the IP source material.

Figure 11.2 (Johnson 1984), shows a pseudo section, derived from pole-dipole array time-domain IP measurements. In this figure, the microcomputer derived Cole-Cole parameters have been plotted. The time constant τ clearly differentiates an auriferous zone of disseminated pyrite (small τ) at the north end of the line from a pyrite-bearing iron formation (large τ) which lies between 400s and 500s.

A new and interesting departure from the field instrumentation of Photos 11.1 and 11.2 is offered in Photo 11.4. Here we see the incorporation of a lap-top, battery-operated microcomputer into a portable, high resolution 12/24 channel seismic receiver. The microcomputer controls the operation of the receiver, and processes and records the 1024 channels of digital data from each of up to 24 geophones.

The chief advantages of this approach to instrument development, versus the use of a custom designed microprocessor-based system, include:

- forward compatibility with future developments in lap-top microcomputers
- flexibility and speed in programming, using a high level language
- availability of the microcomputer in the field for on-site data storage, and data processing, and for later off-line interpretation and presentation.

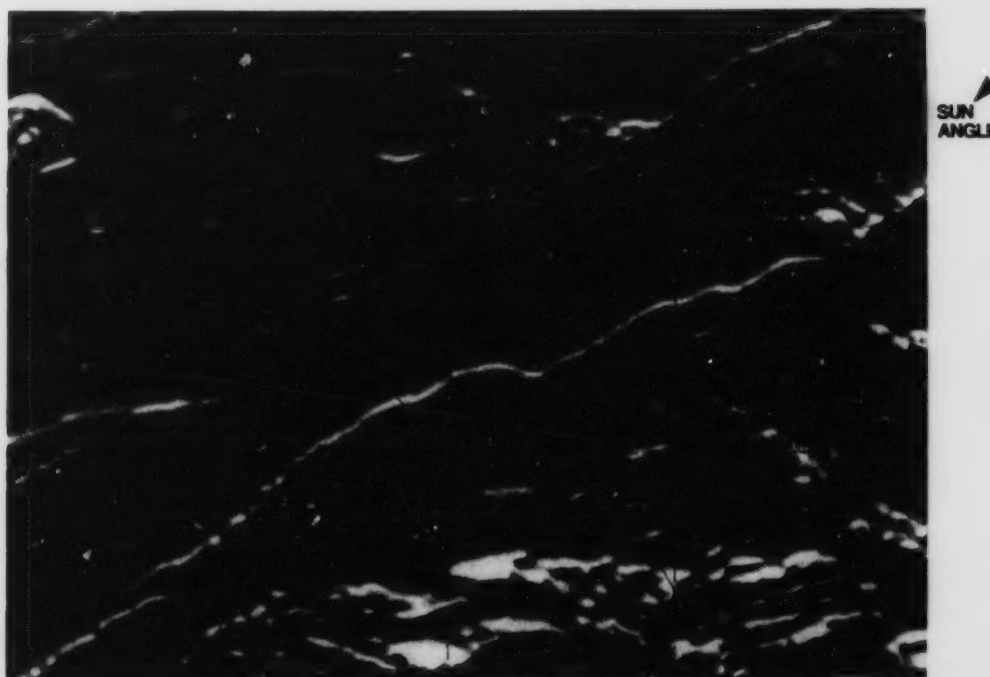


Photo 11.3a. Northwest Ontario; monochrome representation of aeromagnetic data with a northeast sun illumination angle.

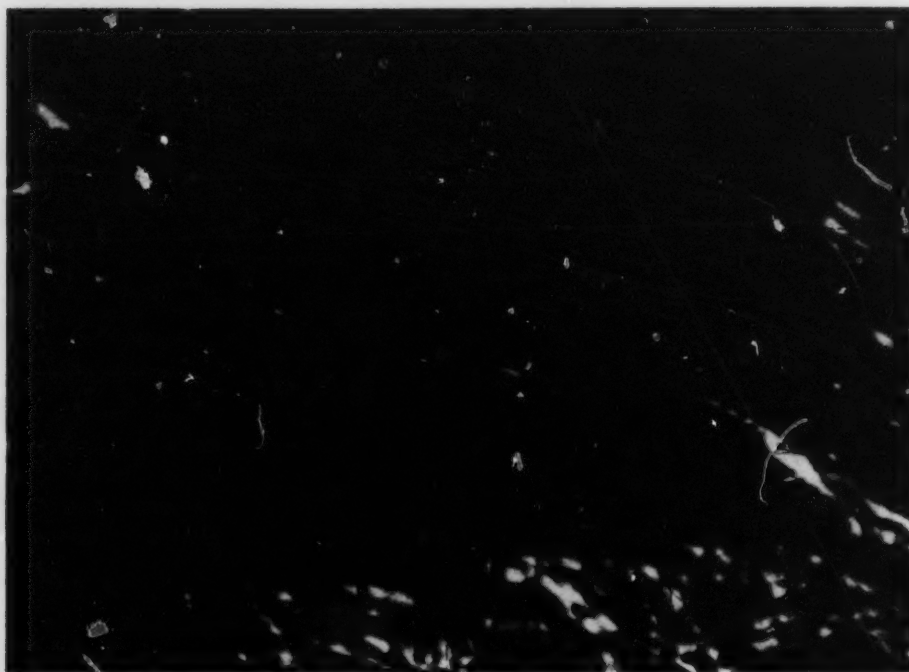


Photo 11.3b. Same data with a north sun illumination angle (courtesy of Dighem Surveys and Processing, Incorporated).

DIRECT DETECTION METHODS

Most mining geophysical methods employed today are indirect methods. That is, at best, they provide information relating to the distribution in the earth of one or more physical properties. The relationship between these physical properties and any particular type of mineral deposit being targeted, is usually an indirect one and often of low statistical validity. One well known exception to this statement is in gamma ray spectrometry, wherein the presence, and often the grade of the naturally occurring radioactive elements (K, U, Th) may be directly deduced.

Changes are constantly taking place in the economics of mineral commodities. These changes may result in a shift of interest from certain types of ore deposits to others, for example, from porphyry coppers to high-grade massive sulphide deposits, or from base metals to precious metals. In addition, there are important changes taking place in the technologies of metal alloys, electronics, and superconducting materials. As a result, exploration attention may be focused on hitherto uninteresting or even exotic metals such as gallium, germanium, lithium, yttrium, lanthanum, etc. Explorationists may then be called upon to find large-scale deposits of these new metals for their supply in the years to come. Consequently, the geophysicist will be challenged to develop exploration tools suited to the detection of the

deposits of metals which are economically important at the time.

Even skilled geologists may encounter difficulties in visually detecting and quantifying more than a relatively small number of common types of minerals related to ore deposits. This limitation has long been acknowledged in the case of uranium exploration, where it is well established that one must rely on gamma radiation devices as a primary exploration tool, despite their inherently very shallow (20 to 30 cm) depth of detection. Other mineral deposits which are often difficult of visual discernment and quantification include those of tungsten, tin, gold, rare earths, etc.

Fortunately, several types of geophysical techniques already exist, in various stages of development, which may advantageously supplement the eye of the geologist. Aside from gamma ray spectrometry (mentioned above), these techniques are not as yet widely used. They include active-source nuclear analytical methods for direct elemental analysis *in situ*, and both passive (reflectance spectra) and active (fluorescence) techniques for direct mineralogical analysis.

NUCLEAR ANALYTICAL TECHNIQUES

Portable x-ray fluorescence (XRF) analysers, using artificial isotopic sources, can be used to obtain elemental analysis of geologic materials *in situ*, even at concentration levels which are, for many elements,

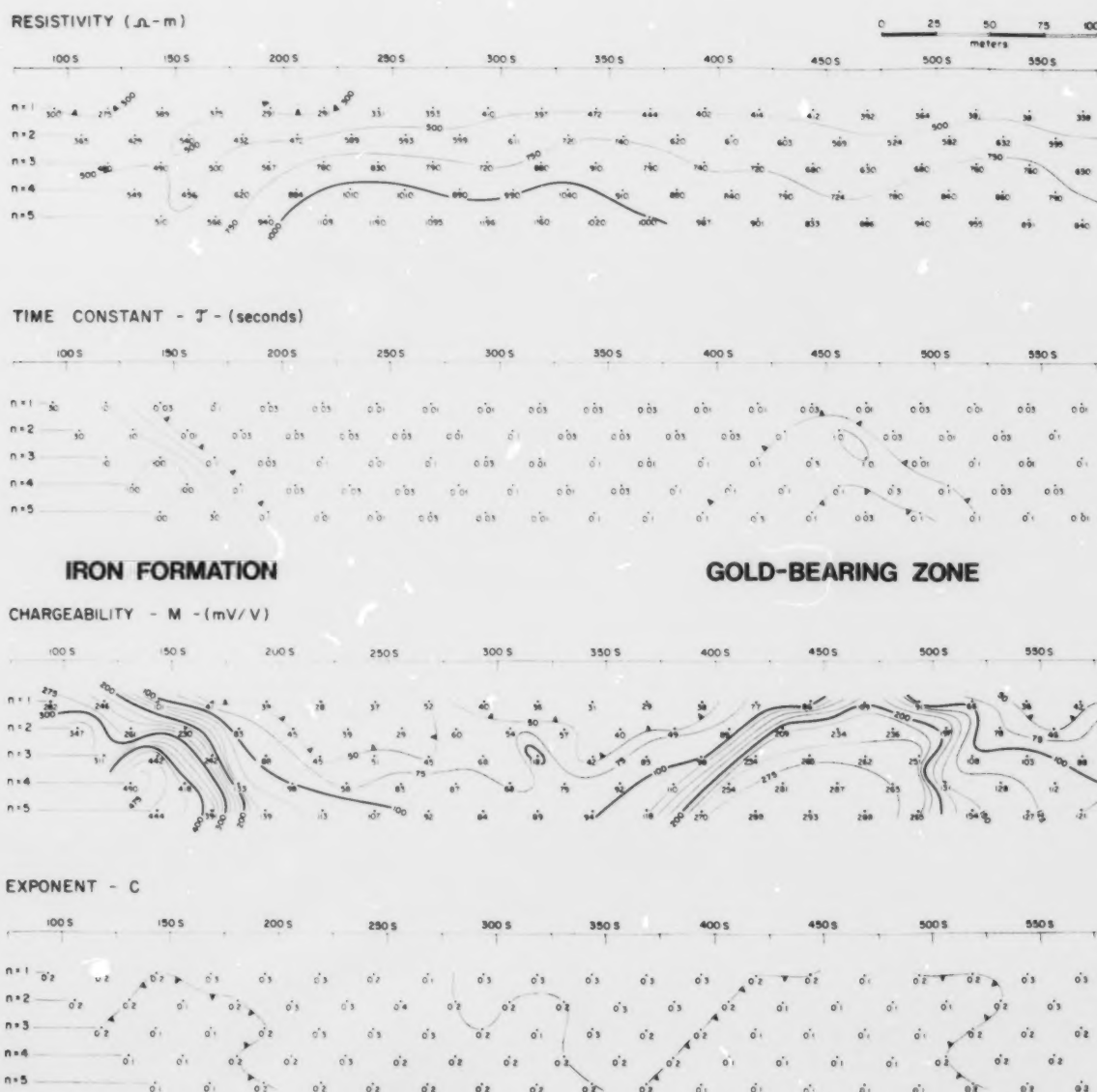


Figure 11.2. Geraldton, Ontario; pole-dipole array 50 m spacing, time-domain IP measurements, presented in pseudo section form in Cole-Cole parameters M , τ and C (after Johnson 1984).

much lower than economic ore grade. The sampling depth of XRF measurements is, however, only a millimetre or two, so that they lend themselves best to surface prospecting and to grade control of mine faces. They are somewhat less well adapted to borehole logging, where they require dry, clean holes, (see World Mining Equipment 1987).

There are, however, other nuclear analytical techniques, in particular neutron-gamma analysis, which can yield essentially bulk sample elemental assays, because their sampling depth is of the order of up to 20 cm.

Figure 11.3 (after Mikesell *et al.* 1986) shows two logs of manganese obtained by neutron activation (delayed gammas) measurements in a borehole, compared with the chemical analysis of the core. Despite the different gamma ray detectors employed on the two logs, both show a reasonable correlation with the chemical analysis, even though the manganese content does not exceed one percent.

Figure 11.4 (after Nargolwalla *et al.* 1976) provides a comparison between copper grades in a borehole in a porphyry copper deposit, obtained using neutron-prompt-gamma logging and those ob-



Photo 11.4. 12/24 channel portable seismic system using lap-top microcomputer for operation and recording.

tained through chemical analysis of the core (incompletely recovered). It can be seen that the relationship between the two data sets is very good, even though the mean grade in this section of the hole was less than 0.25 percent copper.

Some active nuclear analytical techniques are highly developed and widely applied in the Soviet Union, but have not yet found wide acceptance in the west. Their acceptance will likely come in due course because, when coupled with the use of inexpensive non-coring drilling techniques, they may provide a cost-effective alternative to diamond core-drilling and chemical assaying.

Neutron gamma techniques are most compatible with borehole logging, since the neutron source is well shielded from the operator by the rock around the hole. In addition, since the nuclear assay is representative of a much greater volume of rock than the core itself, the grades derived from the nuclear measurements may be statistically more meaningful than those derived from a chemical analysis of the core.

All of the active nuclear techniques provide responses that relate to the total elemental content of the rock, regardless of the compound forms in which each element occurs. This may be advantageous at most times, but is, at other times, inadequate. The same element may be present in two compound

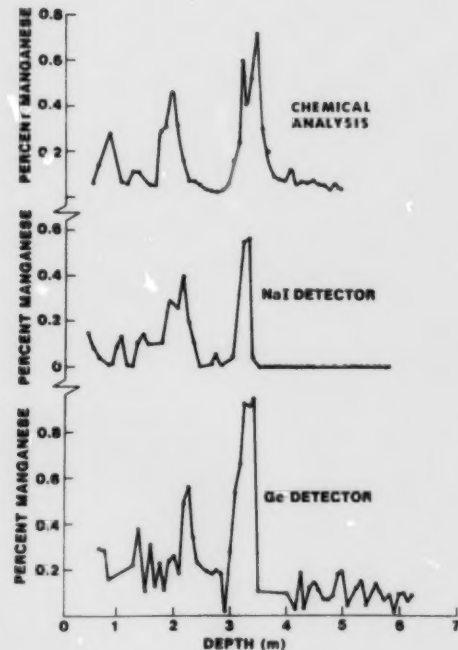


Figure 11.3. Neutron activation measurement of manganese in a borehole compared with chemical analysis of core (after Mikesell et al. 1986).

forms in the same rock mass, (e.g. in sulphides and silicate form), one of which is amenable to the prevalent metallurgical treatment and the other is not.

All active nuclear analytical techniques require close contact between the radiation source and the rock mass being investigated, both for the sake of safety from stray radiation and because of the intrinsic geometry and sensitivity limitations of the detector.

Whereas no one active analytical technique responds equally well to all rock-forming elements, there is such a variety of these techniques that we can usually select one which will satisfactorily determine the content of a desired element in the specific geologic matrix.

OPTICAL ANALYTICAL TECHNIQUES

Moving to the optical region of the electromagnetic spectrum, we find that there are very interesting advances being made towards the use of UV-visible-IR radiation for the detection and quantification of specific minerals. For example, the analysis of solar reflectance spectra, particularly in the near-IR portion of the spectrum, may provide information concerning the presence of certain ferrous, carbonate, clay alteration, and ammonia-bearing minerals. Certain of these minerals are commonly found in alteration zones related to mineral deposits.

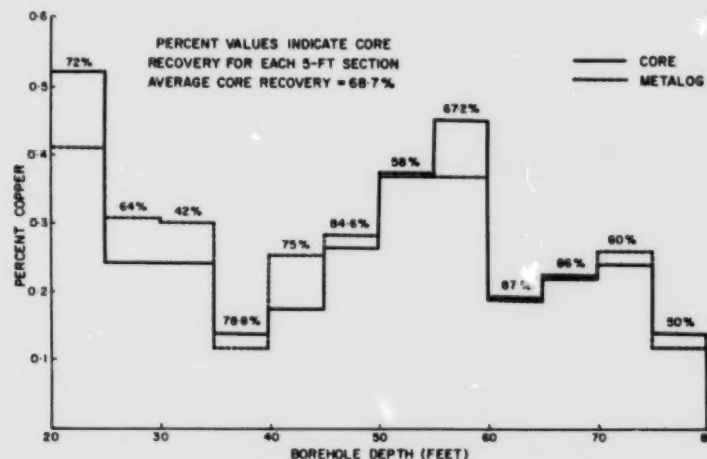


Figure 11.4. Neutron-prompt-gamma measurements of copper in a borehole compared with the chemical analysis of cuttings. Five foot sections averaged. Logging speed 13.5 m/hr (after Nargolwalla et al. 1976).

In theory, these reflectance spectral features could serve to remotely identify the minerals in question, provided of course, that reflectance data was obtained with sufficient resolution across the spectrum and that 100 percent of the field of view was occupied by one pure mineral species only.

Multi-channel spectral radiometers may thus, in principal, be used on the ground, from aircraft, and from satellites (Rowan et al. 1987), to map the surface distribution of minerals by virtue of their differences in solar reflectance spectra. Problems arise, however, when there are mixtures of minerals in the instantaneous field of view of the radiometer, or when the radiometer has too few channels to make a mineral determination with high probability. Surface and airborne spectral radiometers currently have good spectral resolution, with up to 128 spectral channels available, but satellite multi-spectral scanners currently only have up to eight channels. By 1994, 32 channels may be available (Landsat 7) and 128 channels are being proposed for the EOS Polar Orbiter at a later date (Voute 1986).

An additional identifying characteristic of certain minerals is their photoluminescence. Under optical excitation the spectral and lifetime characteristics of their photoluminescent emission spectra, taken in combination, may provide a novel and highly specific technique for their identification.

Some of these photoluminescent minerals may be of direct interest as ore minerals (for example, scheelite or hydrozincite), while others may act as pathfinders, typifying the presence of certain types of ore deposits such as those of gold, tin, and molybdenum.

Through the laboratory quantification of these diagnostic characteristics of mineral photoluminescence, a method designated as Luminex, has been

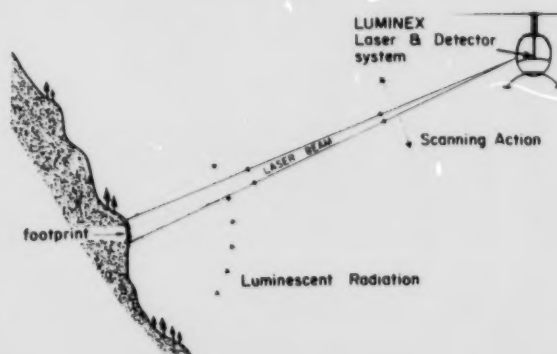


Figure 11.5. Schematic representation of aerial system employing laser-induced luminescence for mineral detection (after Robbins and Seigel 1985).

developed for the detection and semi-quantification of these minerals in the field (Robbins and Seigel 1985). The method may be employed on the ground using a hand-held analyser for detailed surface application and may also be used for aerial reconnaissance by means of a high-powered Excimer UV laser excitation source (Figure 11.5).

Figure 11.6 shows a section of a grid of lines which has been surveyed by a helicopter-borne Luminex system in the southwestern U.S.A., over an area with some zinc showings. For this presentation, the original aerial field data has been computer interpreted to derive semi-quantitative luminescent mineral identification. Responses attributable to hydrozincite have been plotted in terms of "equivalent percent" by exposed area.

We have thus seen that there are a variety of methods and devices, based variously on nuclear,

optical reflectance and photoluminescence phenomena, which will, in the near future, increasingly help meet the explorationist's need to provide an increase in the range of mineral deposits of economic interest which are detectable by geophysical means. These methods are in various stages of development and introduction into practice at the present time.

It is also noteworthy that all of these methods are made practicable, primarily through advances in microelectronics for use in data gathering; and advances in computers for data processing, interpretation, and presentation in terms of the elemental or mineralogical composition of the rock.

MULTI-METHOD SURVEYS

It seems obvious that the more independent geophysical information that we may obtain, the better will be our ability to interpret the subsurface geology. The addition of yet another geophysical sensor to an

existing array of sensors will, however, only be warranted if the additional sensor yields new, independently useful, and cost-effective data, that is, the benefits of the resultant additional data in the prevailing geological environment outweigh the additional cost of acquisition and processing.

In the case of airborne surveys, the incentive to add yet another sensor is usually clear, providing that the added sensor is compatible with the pre-existing ones and that it does not require a change in the flight conditions (terrain clearance, ground speed, permissible flying weather, and ambient noise) or aircraft type, etc.

Helicopter-borne geophysical systems lend themselves well to multi-sensor installations, since those sensors which are likely to be affected by the proximity of the helicopter or by one another may readily be towed by cable from the cargo hook of the helicopter. Plate 11.1 (see Colour Folio near end of book) shows such a multi-sensor system of

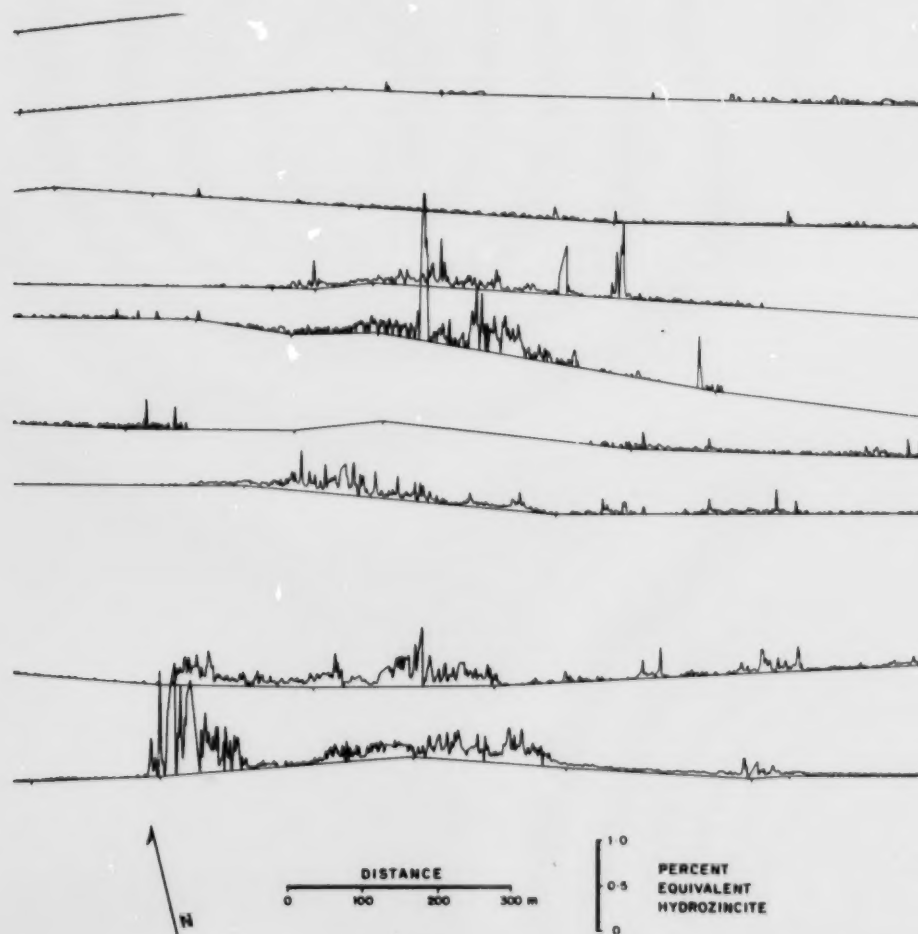


Figure 11.6. Section of aerial Luminex grid in southwest U.S.A. showing presentation of interpreted equivalent percent hydrozincite.

recent origin. In this case, it includes two cesium magnetometer sensors, yielding both total field and vertical gradiometer measurements, a rigid, 6 m separation electromagnetic system, including three transmitter/receiver pairs, each operating at different frequencies; a total field VLF receiver receiving signals from up to three stations simultaneously, and a 1024 channel gamma ray spectrometer with a 17 litre crystal detector. All of these data are recorded ten times per second on magnetic tape.

In the case of ground surveys, the decision to add yet another sensor is more complex than for airborne surveys. Different ground methods are rarely totally compatible in field procedure and normal time of measurement, etc. In addition, controlled source methods (electromagnetic, IP, and seismic, for example) require the addition of an excitation signal source, usually demanding additional personnel for transport and operation. Nevertheless, as Photo 11.1 illustrates, it is, for example, highly cost-effective for an operator to make magnetometer total field and gradiometer, VLF, and controlled source electromagnetic measurements (fixed source or moving source) on a single traverse over the ground.

As the exploration sequence in any area progresses to ever greater depths, the cost of even one long, misdirected borehole becomes so great that every additional, useful, and independent piece of geophysical information justifies the cost of its gathering.

BOREHOLE LOGGING METHODS

Inevitably, the late stages of exploration entail the drilling of boreholes to investigate a subsurface region of interest indicated by surface geophysical, geochemical, or geological information. These boreholes are commonly drilled using coring techniques, usually with diamond drill bits. Drilling techniques are all expensive and they often absorb more than 75 percent of the total budget of deep exploration programs.

The opportunity exists to use these expensive openings for geophysical measurements, which will not only greatly enhance the value of the drillholes, but will also help to justify the cost of their creation. Borehole logging has the potential to form a very important pillar of mineral exploration practice, but it has not yet been fully accepted by the mining industry as a whole. There is, in fact, a broad range of borehole logging technology which is more or less developed and field tested at the present time, but which is not as yet routinely applied to mineral exploration.

Downhole logging methods, including a variety of active and passive nuclear techniques, electric, and magnetic measurements, can yield the physical properties and even the grade of specific elements in

the immediate vicinity of the hole (Figures 11.3 and 11.4). The fact that these techniques have been available for many years but not put into general use, is largely a reflection of the fact that there has been no accepted need for them when core drilling has been employed. The exploration geologist usually feels that the core (when recovered) contains all the essential information that he requires, and therefore downhole geophysical measurements are redundant. Core drilling is, however, more costly than non-coring drilling, and it is often justified primarily by the need to obtain rock samples for geological or grade information. In many instances the use of non-coring techniques, coupled with borehole logging, for both exploration and development drilling, would result in a substantial reduction in overall cost, while yielding equivalent, if not better, geological information. In addition, core recovery is rarely 100 percent complete, and may be very incomplete in areas of faulting or shearing, which are often of great economic interest.

A more optimistic forecast for adoption applies to remote geophysical detection in boreholes, that is, to methods which utilize the boreholes to provide access, at depth, for sensors which can remotely detect the presence of certain types of mineral deposits (or environments favourable for those). These methods are, in effect, adaptations of surface geophysical prospecting methods, such as electromagnetic, induced polarization, seismic, and magnetic. The range of detection which these methods may achieve from the hole is usually comparable to their normal depth of penetration when they are used in their surface modes. By their use, they may in effect, increase the volume of rock to be explored by a factor of up to 10 000 relative to the core itself.

As the cost of deep exploration drilling rapidly escalates, the trend toward remote detection logging will undoubtedly accelerate, eventually to become a routine adjunct to deep drilling itself.

THE SEISMIC METHOD

The seismic method, which has been developed to a high level and has long held primacy in the realm of petroleum exploration, has made little contribution to date to mining exploration. The reasons for this are evident. The apparatus, field procedures, and interpretation technology of the seismic petroleum industry have been oriented toward deeply buried structures (1 to 10 km in depth), which are essentially horizontally stratified. Mining problems rarely involve such depths and structures.

In addition, crystalline rocks have relatively high velocities, which usually display only small differences from one rock type to another. Moreover, geologic structures of interest in mining often are very complex, intensely folded, faulted, and cross-cut by intrusive rocks. Only the most determined and well-financed mining exploration manager

could countenance the high cost of employing a full-scale petroleum seismic crew on his exploration program. Exceptions have occurred, however, where geologic targets at great depth are associated with major basins, for example in the case of the Witwatersrand Basin (Pretorius and Jamison 1987) and the Sudbury Basin.

The advent of portable multi-channel seismic receivers (e.g. Photo 11.4) has changed the situation. These devices are low-cost, high-resolution (as little as a metre or so), readily field-portable, and useful for both refraction and reflection surveys. They are thus geared to the same geologic and economic scale as are most other mining geophysical methods. These receivers may be employed for surface surveys and borehole logging as well. Single boreholes may be logged, or logging may take place using dual boreholes, one for the source and the other for detection.

Whereas the interpretation of the seismic responses of three-dimensional mining structures may well be complex, much can be utilized from the extensive library of petroleum interpretive technology.

The exceptional spacial precision of the seismic method is a great incentive to its adoption into general use in mineral exploration.

Figure 11.7 shows the application of the portable shallow seismic receiver of Photo 11.4 to gold exploration in Canada. In this example, the reflection seismic information is being utilized to indicate both the location of the bedrock under the glacially derived overburden, and the position of tills on the bedrock. These tills would then be sampled by boreholes to determine if gold-bearing zones occur in the area. In this figure the "optimum common offset reflection profiling technique", developed by the Geological Survey of Canada, has been employed in the field (Pullan *et al.* 1987).

ADVANCES IN SUPERCONDUCTING SENSORS

Major advances are now being made in the development of higher temperature superconducting materials. It is reasonably certain that such materials, operating at temperatures above that of liquid nitrogen, will be developed and brought into commercial use

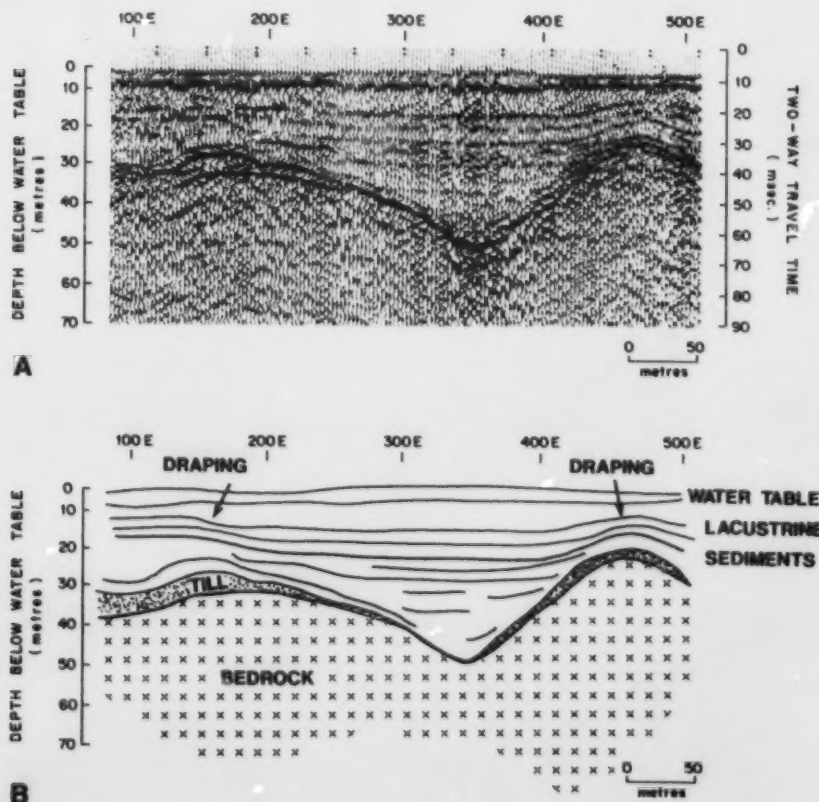


Figure 11.7. Portable shallow seismic profile, Val Gagné area Ontario -

A. Common offset seismic profiles.

B. Interpreted section. Both bedrock and till create strong reflections (data provided by the Geological Survey of Canada, processed and presented by Scintrex Limited).

shortly. Such materials will have significant impact on geophysical sensors, in particular on SQUID (superconducting quantum interference device) magnetic sensors, inexpensive compared to liquid helium, which is being used at present. In addition, these materials may facilitate the use of superconducting gravimeters based on magnetic levitation.

POSITIONING SYSTEMS

The ultimate in continuous, precise, all-weather and all-terrain, worldwide positioning systems will be in place early in the next decade. It is the GPS or Global Positioning System, to be based on a series of 18 transmitting satellites, in evenly spaced orbits, 20 200 km above the earth. Each satellite will transmit on two frequencies simultaneously to permit a correction to be made for atmospheric refraction errors. When all 18 satellites are in place, a user will be able to receive signals from four or more satellites simultaneously. By making time-of-arrival measurements on these signals, the user will be able to determine his latitude, longitude, and altitude.

The achievable precision of determination of these positional co-ordinates will depend on the receiver equipment used and the extent to which access to the higher precision transmitting code is made available to civilian users by the U.S. Department of Defense. It is clear however, that in absolute terms, using a single receiver, better than 5 m accuracy 50 percent of the time, will be feasible and even much higher accuracies will be achievable (to some centimetres) relative to a fixed receiving station that one may establish in the survey area.

For aerial surveying the availability of GPS will bring a number of important benefits. Firstly, the co-ordinates of the survey aircraft (horizontal and vertical) will be provided, essentially on a continuous basis. This will not only improve the survey navigation and reduce its cost, but will also simplify and expedite the data compilation and presentation through eliminating the tedious and error-prone manual steps of the flight path recovery and digitization.

A further benefit of GPS is that it will provide a permanent, reusable, positioning reference. Surveys done at different times in the same area may be precisely correlated in position. In addition, portable GPS receivers will enable ground surveys to use the same positioning reference, and therefore to locate themselves accurately relative to targets indicated by the airborne surveys. It could even become feasible for drillhole positions to be located on airborne references without having to carry out a ground geophysical survey beforehand in order to determine their precise location.

On ground surveys, the GPS co-ordinates may be input directly from the GPS receiver into the digi-

tal memory of the geophysical receivers (such as those in Photos 11.1, 11.2 and 11.4, etc.) thus rendering the processing and presentation of the geophysical data even more automatic.

IN REVIEW

It is clear that advances in microelectronics, computers, sensor technology and satellites, will increasingly contribute to the effectiveness of the mining geophysicist in all aspects of his work in the years to come. These advances will help to produce data of higher quality and greater diversity, at little additional cost, and will broaden the range of mineral deposits that we may detect.

ACKNOWLEDGMENTS

The author is indebted to the sources named for permitting the reproduction of the various illustrations attributed thereto. Where a specific source has not been named, the source material is from Scintrex's files.

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12. Exploration for Extraterrestrial Resources

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ABSTRACT

As man begins to carry out more and more activities outside the confines of earth's gravity, he has begun to assess the question of the use of resources from the moon or from earth-crossing asteroids. The energy requirements to remove material from the moon or to retrieve material from an asteroid are quite low when compared with the energy required to bring material from the earth.

Material needs for space activities can be categorized in several ways. Long space missions may require simple aggregate material for shielding from radiation or for thermal control. The moon's surface is a powdered aggregate and could easily be mined or excavated for this purpose. Large space structures are likely to require materials such as silicon, aluminum, titanium, magnesium or iron. These occur in abundance on the moon's surface with varying concentrations from the mare regions to the highlands. Metallurgic plants could be set up to carry out the

necessary extraction. Solar wind gases occur in the soils in substantial quantities.

The moon is characterized by rocks which contain no water. Hence the processes that form most terrestrial ore bodies cannot have operated on the moon. It is possible, of course, that there will be magmatic concentration of precious materials and there may be local regions where exhalative deposits may occur.

An exploration strategy for the moon would be quite different than one on earth but geophysical and geochemical methods can be applied in modified form.

A number of asteroids can be reached quite easily. If their compositions are similar to those of meteorites, we can expect to have iron-nickel asteroids with appreciable amounts of elements such as cobalt or chromium. Other asteroids may be like carbonaceous chondrites and contain water in significant quantities.

Geophysical Methods: Advances in the State of the Art



13. Accomplishments of Wide-band, High-power EM

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ABSTRACT

This review focuses on EM applied to mineral exploration, but includes developments in related fields such as hydrocarbon exploration and crustal geophysics as they are likely to significantly impact mineral exploration during the next decade. EM surveys are now routinely applied to the search for large, localized mineral targets at depths of several hundreds of metres. In sounding mode, extensive conductive layers are commonly defined by EM systems at depths up to several kilometres.

Wideband instrumentation is now widely used for fixed- and moving-source systems, both in the frequency and time domain. Increasing use of fixed-transmitter EM to maximize dipole moment has become standard for deep penetration surveys. A number of high-power ground EM systems became available in the early 1980s.

Processing, modeling, and interpretation schemes have been slow to adapt to the large quantities of EM data now being collected. Type-curve matching and use of simple characteristic point rules for single time/frequency data is still the norm for interpreting EM, although the use of interactive computers with simple (plate) modeling algorithms is becoming more popular. Concepts such as smoke rings in the time domain, and colour movies of EM diffusion are becoming increasingly important in aiding modeling and interpretation.

For EM sounding, advanced processing tools such as nonlinear inversion of data to fit layered earth models are in routine use. Recent developments in data processing have presented less computationally expensive methods for transforming field data to conductivity-depth imaged sections.

INTRODUCTION

This paper is based on a short review of the state-of-the-art of high-power EM in mineral exploration which was presented at Exploration '87. Electromagnetics (EM) as applied to geophysical exploration is a topic of major research, with over 600 papers published in the geophysical literature during the period between 1977 and 1987. In selecting which achievements to discuss in this review, we have attempted to use current practice in North America and Australia to guide in our assessment of the significance of the published literature. In preparing this paper both for

presentation and publication, we found it very difficult to balance the need for a comprehensive review with the requirement to evaluate the most productive of current and future trends.

OPERATIONS AND INSTRUMENTATION

Physical properties affecting EM propagation and diffusion include the spatial distribution of the conductivity σ , the magnetic permeability μ , and the dielectric permittivity ϵ . In mineral prospecting, the frequencies/time delays used are such that the diffusion process is dominant, and the conductivity parameter is the most important of the three above. However, the conductivity structure of the ground is less well constrained by measured data than is the conductance structure (Fullagar and Oldenburg 1984). Conductance is the product of local conductivity with a characteristic dimension such as thickness or depth, and conductance structure may for example be the location and conductance of an isolated feature or the cumulative conductance of a layered earth as a function of depth. Historically, airborne and ground EM techniques have been mostly applied in the search for targets extending within 100 m or so of surface. With much of the recent emphasis in mineral exploration towards shallow deposits of precious metals, much of the current EM exploration effort involves routine use of traditional and inexpensive techniques such as VLF and slingram (loop-loop) surveys.

Source Types

Significant improvements in wide-band capability, transmitter power and flexibility of multicomponent acquisition have been developed for moving source-moving receiver frequency domain EM (FEM) systems such as the MAXMIN I (Betz, Consultant, Toronto, personal communication, 1987) and Genie (Johnson and Doborzynski 1986). The search depth of the slingram type systems has been extended well past 200 m in some applications. In environments with variable conductive weathering, such as much of Australia, the depth of penetration of high frequency EM systems, which were originally developed for operation at frequencies f in the spheric noise null around 2000 Hz, is limited both by the small skin depth of diffusion $\delta = \sqrt{1/\sigma\mu\pi f}$ at these high frequencies, as well as the significant transmitter receiver separations d used which result in a large overburden response as indicated by the d^2 term in

the induction number $\sqrt{2\pi f \sigma d^2}$ (McCracken *et al.* 1986). To solve these problems, the use of "coincident loop" geometry transient electromagnetic (TEM) systems with a capacity to operate at low base frequencies and measure to late sample times (e.g. SIROTEM) have become established as a routine exploration tool.

In base-metal and uranium exploration applications, more powerful EM surveys using large loop sources are now routinely being applied to the search for large, localized mineral targets at depths of several hundreds of metres. In the deeper parts of the Athabasca Basin of Saskatchewan for example (McMullan *et al.*, see Paper 42, this volume), discoveries have been made of economic mineralization associated with conductive graphitic metasediments below 400 m of sandstone cover, and strong EM anomalies have been detected at interpreted depths to source of over 700 m. Figure 13.1 shows an example of a successful Crone DEEPEM survey associated with the discovery of the Cigar Lake uranium deposit (Fouques *et al.* 1986) beneath over

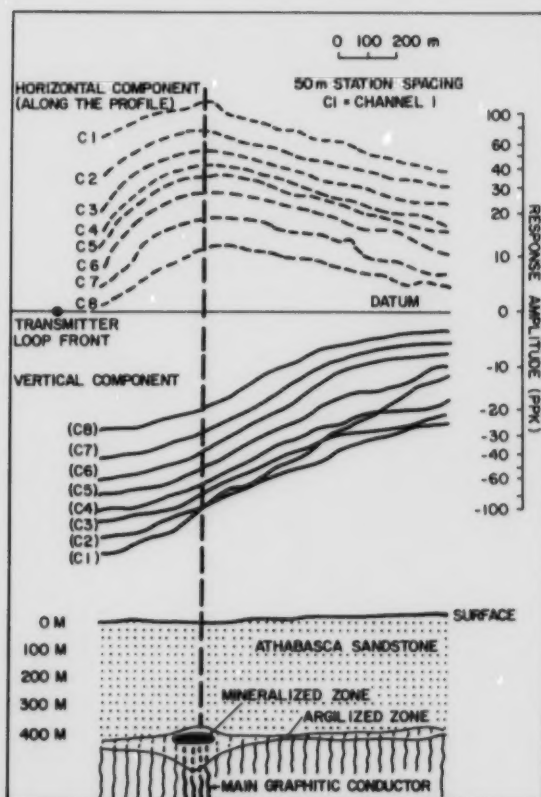


Figure 13.1. Discovery Deepem profiles over the Cigar Lake Uranium deposit in Northern Saskatchewan. A significant background response has displaced the vertical component crossover point from being zero above the conductor (after Fouques *et al.* 1986).

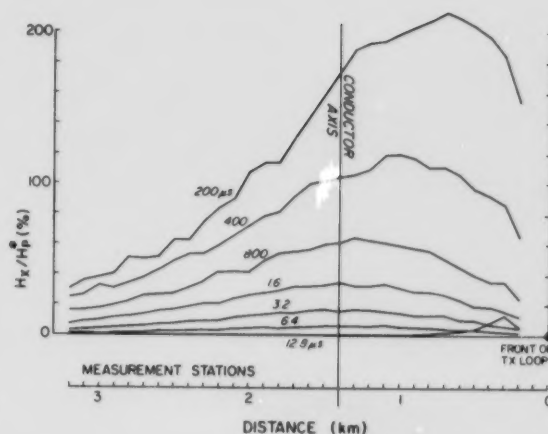


Figure 13.2. UTEM horizontal component data point normalized to the strength of the primary field at surface above the conductor axis over a conductor interpreted to lie beneath 700 m of resistive sandstone. Note the extreme survey line length needed to define the peak location at late delay times.

400 m of Athabasca basin sandstone cover. Figure 13.2 shows an example of UTEM (West *et al.* 1984) data collected over a conductor beneath an interpreted 700 m of resistive sandstone cover in this general vicinity. Note that the survey line of several kilometres in length is required to obtain lateral resolution of the broad anomaly from such a deep source. Known sulphide conductors have been detected in test surveys at depths in the 400 to 500 m range in both resistive terrains and terrains covered with conductive rocks/overburden. In sounding mode, extensive conductive layers have been defined by EM systems at depths of several kilometres.

Survey Practice

During the last decade there were no fundamental changes in the nature of EM instrumentation used in the mineral exploration industry. However there were several significant changes in routine EM surveying operation. Primarily, there was a growing acceptance of the interpretational necessity for wideband systems whether operated in time or frequency domain, and almost all instrumentation for both fixed and moving source systems has now become wideband. Increasing use of fixed transmitter EM to maximize dipole moment became standard practice for deep penetration surveys. For detailed surveys, collection of multicomponent data at each receiver site from a number of different transmitter locations became an increasingly common trend (Irvine and Staltari 1984; Macnae and Lamontagne 1987).

Instrumentation

A number of high-power ground EM systems became commercially available in the early 1980s; and

since then voltage/current limits have increased on individual systems. No major changes occurred in available airborne EM system transmitters. In EM receivers, some wide-band instruments, such as the A-cubed airborne receiver (Annan 1986) as well as a research system (Duncan *et al.* 1980) using a pseudorandom binary source (PRBS) can produce their output in virtually any form in time or frequency domain for convenience of modeling and interpretation. Figure 13.3 shows in block diagram the signal processing tasks of the A-cubed digital programmable receiver to produce a step response output from raw sampled data. This receiver is also used in different mode in the airborne GEOTEM system, which allows for flexibility in location of delay time windows in data acquisition.

Commercially available EM systems are summarized yearly by Hood in the January issue of the Canadian Mining Journal. For mineral exploration, the commercially available high-power TEM systems are the Lamontagne Geophysics UTEM system measuring the step response (either of the electric or magnetic component) and the SIROTEM, Geonics EM37 and EM42, the Crone DEEPEM and Zonge GDP12 systems essentially measuring the impulse response of the magnetic component. The definition of step and impulse response is based on the shape of the unsampled receiver output resulting from the primary input in the absence of conductors. The proprietary Newmont EMP system is also of impulse-response type. Most TEM systems have an adjustable range of sample times within two or three decades, in some instruments from as early as 10 μ s to as much as several seconds. Figure 13.4 is an example of data from one instrument. Large-loop

FEM systems include the Androtex ELFAST, BRGM Malis and the high-power Scintrex Genie system. The frequency range of these instruments lies in the 0.1Hz to 10kHz range.

Several research systems, including the EM60 frequency domain system at the University of California (Wilt *et al.* 1983) and the grounded source Colorado School of Mines TEM system (Keller *et al.* 1984) are also operating. Almost all commercial mineral exploration systems use purely inductive closed-loop sources rather than grounded wires to aid in the elimination of anomalous responses due to transmitter ground-return current variations. Exceptions to this include applications of controlled-source, audio-frequency magnetotelluric (CSAMT) systems to mineral application and geothermal problems and the long-offset transient electromagnetic (LOTEM) system (Strack 1985; Strack *et al.*, in preparation).

In original concept, (Goldstein and Strangway 1975), CSAMT systems were needed to fill in parts of the desirable MT frequency spectrum in the audio range where the natural source energy was insufficient to obtain good data. The Cagniard definition of apparent conductivity used in AMT relating the horizontal electric E and magnetic H fields perpendicular to each other is $\sigma_a = 2\pi f\mu(|H|^2/|E_\perp|^2)$. This is a "far field", uniform source definition, and to be valid the source is required to be very distant, in practice greater than three skin depths at each frequency of interest. At frequencies where the source is closer than three skin depths, which is commonly

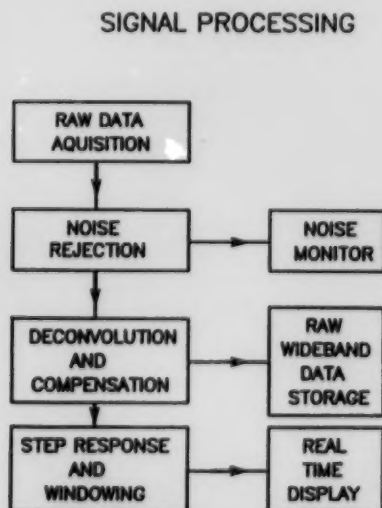


Figure 13.3. Block diagram of a modern airborne receiver processor capable of presenting data in either time or frequency domain (from Annan 1986).

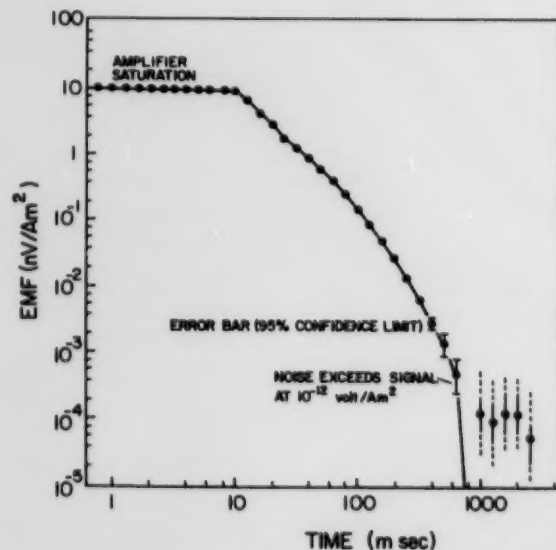


Figure 13.4. Example of data collected with the computer-based EM42 receiver. Although this particular data set has been collected over three and a half decades in delay time, amplifier saturation at early delay times and noise at long delay times has limited the useful data to two decades.

the case for much of the data collected in the resistive terrains common in mineral exploration surveys, the Cagniard approximation fails. In this case, the CSAMT system has to be considered to be a local, controlled-source system and in terms of modeling and interpretation its magnetic component has characteristics similar to other controlled-source EM systems. Interpretation of the electric component is more complicated than the magnetic component, due to charges induced at the high conductivity contrast at the earth's surface and also by induced polarization effects. These effects will not be discussed here for either CSAMT or other systems such as the PRBS and UTEM systems which can also measure electric fields.

Increase in the depth of penetration over the years has occurred through two distinct improvements in technology: in increasing signal strength, and in decreasing the effects of noise. A commonly used measure of the transmitter strength is the "dipole moment" parameter, consisting of the product of the RMS current and the total area of the transmitter loop. Typical values of dipole moment achieved in current survey practice are around $3 \times 10^6 \text{ Am}^2$ for the commercial large loop systems. High-power transmitters are available that will allow for about a factor of 10 or 20 increase in dipole moment from large loops, particularly if rapid rise-time is not critical. Some efforts have been made to achieve extreme currents with the use of magnetohydrodynamic (MHD) technology, and test transmissions of over 7000A into a 200 m x 250 m closed loop have been realized (TLE 1987). The peak dipole moment of $4 \times 10^8 \text{ Am}^2$ is nearly two orders of magnitude greater than typical commercial transmitter moments, however, the RMS dipole moment of the MHD is less than 10^5 Am^2 , or over an order of magnitude less than commercial EM systems, due to the very infrequent pulse repetition rate. The same peak dipole moment can be achieved by using very large loops and lower power transmitters, with the advantage of continuous transmission. Due to very limited portability and low RMS dipole moment, the MHD systems are unlikely to have a significant impact on mineral exploration.

Waveform Considerations

There is some debate in the literature (e.g. McCracken *et al.* 1986) as to the relative merits of various waveforms in EM exploration, both in time and frequency domain. Mathematically, provided the earth can be regarded as a linear system, perfect data continuously sampled over all times or frequencies with source energy at all frequencies can be exactly transformed to the response that would be measured with any other desired waveform. Thus, for truly wideband system responses measured in the absence of noise, there is no fundamental difference between data measured with any waveform. How-

ever, differences do occur between practical systems because of different signal amplitude and bandwidth limitations, and because data is collected at a finite number of time windows or discrete frequencies in the presence of noise, noise whose spectrum may vary considerably as a function of geographical location and time.

For the purpose of modeling, data is ideally reduced to one of the simplest excitation responses, usually either the step or impulse response in time domain. Data transformation programs exist for this purpose; for example ramp turnoff (Raiche 1984) and "loop effect" correction in impulse response systems or conversion of square wave response to step response (Eaton and Hohmann, in press). Transformation of sparse frequency domain model data to the time domain can be performed with care (Holladay 1981), but no clear analysis has been published concerning the characteristics of transforming non-random noise as well as desired signal. Accurate transformation between step and impulse response data is difficult with field data due to the quite different shapes of their respective signal spectra, and at times part of the transformed response can be dominated by the effects of noise if care is not taken to assess bandwidth limitations.

It is important not to confuse questions of presentation choice, such as whether data are presented as step or impulse response, with measurement issues dealing with the relative merits of practical systems. No comprehensive public comparisons of EM systems exist, due no doubt to commercial sensitivity, although some comparisons of systems in specific environments are available, such as the publication on the geophysics of the Elura orebody (Bulletin of the ASEG, Volume 2, Number 4).

In a practical system, power considerations dictate that for data acquisition in some desired bandwidth, the signal power spectrum should be adjusted to obtain maximum signal/noise ratio in that bandwidth. The desired bandwidth is of course a function of conductivity or induction response parameters and hence of geology, and the noise may be quite variable. Most practical systems have been designed to measure directly the response desired for interpretation within certain bandwidth considerations, and have relied on a simple brute force approach to increase signal rather than optimization of the S/N ratio.

One TEM system (UTEM) allows for variable tailoring (Macnae *et al.* 1984) of the shape of the transmitted signal bandwidth within fixed total power, and maximum current and voltage constraints by prewhitening and uses exact deconvolution techniques to convert the measured channel data to the step response required for modeling. Some experimental systems exist with noise cancellation using either remote or local reference (Wilt *et al.* 1983; Spies, in preparation).

INTERPRETATION

The Geological Target

Interpretation is defined by Sheriff (1984) in the *Encyclopedic Dictionary of Exploration Geophysics* as the extraction of geological information from physical measurements or models. The determination of an acceptable physical model (without geological constraints) that fits measured data is a physical property determination termed *modeling*. Based on early applications of EM in glaciated terrains, notably the exploration for highly conductive sulphides located in a predominantly resistive host environment, the perceived aim of EM interpretation has often been oversimplified to the characterization of an isolated "target" located within a non-economic "background". In this context, the response of the background, its variations and effect on the response of the "target" has often been called "geological noise" whose only effect is to make modeling of the "target" more difficult for the geophysicist. Current applications of EM to geological exploration are focused as much (if not more) on the environment and regional structure associated with economic deposits as it is with the deposits themselves, and the physical characterization of these is a very important aspect of mineral exploration. The geological interpretation of such effects as surficial conductivity changes due to differences in chemical weathering and variation in physical properties of host rocks are of immense geological significance and form a major part of the interpretable "signal". Even in the case of transported overburden which may have little local relationship to a target, the location of significant concentrations of heavy minerals in basal till deposits or buried stream valleys is of significant geological impact. The geophysical aim of modeling of EM in mineral exploration should include the extraction of the entire physical property structure and not solely the modeling and interpretation of the most conductive part. Palacky (see Paper 15, this volume) for example has made a strong case for the mapping of bedrock geology from variations in the conductivity of weathering products measured using airborne systems.

Processing and Presentation

Modeling and interpretation schemes have been slow to adapt to the large quantities of EM data now being collected on a routine basis in a profiling mode. Other than correcting for instrumental gains and primary field strength, the most common data processing technique applied has been a transformation of data to apparent resistivity, often using an asymptotic approximation. Interpreters of large data sets have had few tools available for presenting data in map form, other than compiling interpreted conductor locations. Usually only a single time or frequency channel is contoured, with the possible prior application of a quadrature filter to convert cross-

overs to peaks. Type curve-matching and the use of simple characteristic point rules is still the norm for modeling EM data in the vast majority of mineral exploration targets, although interactive computer modeling with simple models is becoming more popular.

These programs are designed to help in the modeling of simplified cases when conductors can be considered to be in a resistive environment, as is often the case at late sample times if the target conductance is considerably greater than that of other conductors such as overburden. For isolated conductors fitting can be attempted using a single wire loop approximation (Barnett 1984; Fullagar 1987). Other simple programs using concentric loops (e.g. QUASIPLATE), and one or more eigencurrent distributions (PLATE, Dyck *et al.* 1980; and its offspring such as OZPLATE) are in frequent use in this respect. One recent development allows for the calculation of the EM response of multiple plates including the plate interaction terms (Lamontagne 1987) using program MULTILoop. Although these programs have fairly severe limitations such as requirements for rectangular conductors or zero background conductivity, they can be very useful.

As an example of the use of one such program, Figure 13.5 shows an example of vertical component data collected with the UTEM system in the Northwest Territories of Canada. The field data exhibits two crossover-type responses, however, the response of conductor B (located away from the transmitter loop) is virtually all negative in amplitude. Correlating measured responses over other surveyed lines not shown here, it was determined that conductor A has a much greater strike length than conductor B. The total response around conductor B in this case is shifted by a large negative due to the screening effect of conductor A. After initial modeling using simple rules (Macnae 1985), the strike length of conductors A and B were fixed; and the conductance, depth, depth extent, and dip of both adjusted until a reasonable fit to the data was obtained as shown in the Figure 13.5. Note that this model provides an excellent fit to the data only at later delay times. The earlier delay times in the field data are affected by other poorer conductors not fitted by the two-conductor model shown.

Conductive Environments

The modeling of conductive inhomogeneities within non-resistive environments is a significantly more difficult task than the case within resistive environments (Lajoie and West 1976), and much effort has been made to provide schemes to separate inductive and current gathering effects (Spies and Parker 1984). Some fairly extensive libraries of type-curves exist (Macnae 1985) for cases of conductors under overburden. Simplified modeling of the physical processes involved with conductors in contact, such as conductors in a half-space, have been provided

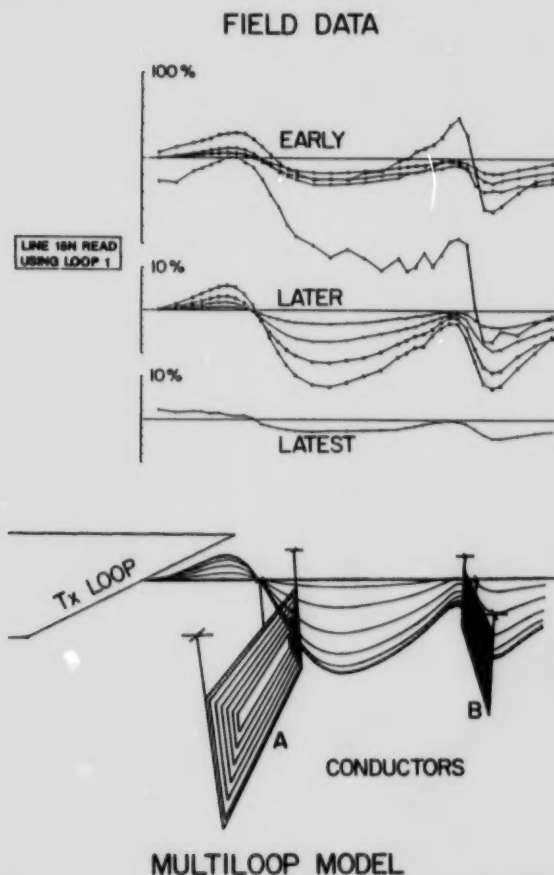


Figure 13.5. An example of UTEM vertical component data continuously normalized to local primary field over a survey line in the Northwest Territories of Canada. The later delay time data has been fitted with a multiple conductor model using program multiloop.

by McNeill *et al.* (1984). The EM response of irregular overburden conductors has been studied using scale models, and a computational method for calculating the response of thin inhomogeneous plates is available (Smith and West 1987). Modeling and interpretation advances have often been the painful result of reinterpretation of "missed" boreholes.

Exact 2-D and 3-D EM modeling have advanced slowly, due to the complexity and ill-conditioning of the numerical formulations, and the computer intensive nature of the solutions. Scale modeling too is tedious and has its own set of limitations, and has not been recently much used in mineral exploration as an interpretation aid. Some full numerical 3-D models are now operational (San Filippo *et al.* 1985, Newman *et al.* 1987) and while 2-D and 2.5-D (Weidelt 1983) models are also available they are chiefly in use in the academic rather than the exploration environment. At the moment, no formu-

lations are sufficiently robust to be used in an unthinking "turn-key" mode for routine model generation. Due to long computation times, most full EM model solutions are used in the forward sense to generate a limited suite of results which can aid in the development of understanding and modeling rules, and also as an occasional check on modeling performed by other means. Although it is possible to implement the full solutions for a plate conductor in a layered earth on computers as small as a PC (Hanneson, Geophysicist, Ontario Geological Survey, personal communication, 1987), preliminary geometrical/coupling calculations take over a week and individual models with varying conductivity only are at best computed overnight on such machines. With rapid advances in the power of desk-top computers, this will likely be an area of rapid advance in the next decade.

Sounding

For EM sounding, advanced processing tools such as non-linear inversion of data to fit layered earth models are in routine use (Anderson 1982; Asten 1987). However, data can often be quite successfully interpreted as a two- or three-layer model by graphical curve-matching techniques. Figure 13.6 is an example of interpretation using graphical master curves, which for convenient normalization are plotted as a late-time asymptotic apparent resistivity (Kaufman and Keller 1983). Although this graphical approach can be very successful, there are significant limitations associated with the late time apparent resistivity as it cannot always be defined (Spies and Eggers 1986), and the current trend is towards computer-inversion, completely bypassing the apparent resistivity computation step. Recent developments in data processing using imaging methods have presented less computationally expensive methods for transforming field data collected in quasi-layered areas to conductivity-depth sections (Macnae and Lamontagne 1987; Nekut 1987; Eaton and Hohmann 1988). These methods may allow for the possibility of limited migration of conductivity anomalies to produce a better conductivity-depth section when lateral inhomogeneity exists.

Concepts

With recent discussions on concepts such as smoke rings in time domain (Nabighian 1979; Hoversten and Morrison 1982), and with the production of colour movies of EM diffusion (Oristaglio and Hohmann 1984; Gunderson *et al.* 1986), the insight of exploration geophysicists into the physics of EM induction in complex earths has significantly improved. The focus of understanding has become the induced currents and their behaviour rather than the measurable but more geometrically complicated electric and magnetic potential fields they produce. It is important to note that the B fields of a current system are simpler to understand than the dB/dt

fields usually measured. The observed data from a dB/dt system can then be thought of as exactly B field data from a conceptual current system which is the time derivative of the actual currents since the magnetic field B from currents dJ/dt is identical to the field dB/dt from current J.

While a start has been made in considering the automation of airborne data modeling (DeMouilly and Becker 1984), due to the complexity and variation of the ground EM geometrical layouts used, as well as the variety of system waveforms, progress in automating EM modeling in general has been slow. Schemes designed for the general interpretation problem are being discussed (Lamontagne *et al.*

1985), and with the advance in computing power rapid progress should be made in this field.

CASE HISTORIES AND ACHIEVEMENTS

Structural and Sounding Applications

When geological information indicates that either a target and/or its environment is shallowly dipping, surveys and data processing techniques have been devised to produce accurate vertical soundings. Horizontal geological layering is mostly confined to sedimentary basins that have not been heavily disturbed in subsequent tectonic activity. Since these basins are the primary hosts for petroleum deposits, EM techniques have been extensively used in sounding mode for hydrocarbon exploration. They have also been used for mapping large hydrothermal reservoirs. There are numerous examples, however, where mineral exploration targets are sub-horizontal and where the EM data can be modeled as a sounding.

Figure 13.6 shows an example of a sounding in Western Australia over a gently dipping mineralized zone at a depth of 431 m (King and Peacock 1985). The zone consists of banded jaspilite, hematite, and barite, with galena and pyrite each locally up to 10 percent. A stringer zone beneath the mineralized zone consists of chloritized silica with chalcocite veins, magnetite, and up to 10 percent combined chalcopyrite, galena, and pyrite. The interpretation was done with the graphical modeling method already mentioned. The modeling and interpretation produce an accurate depth to the top of the conductive mineralized zone beneath the resistive rocks immediately overlying it. Mathematical analysis of sounding data (Fullagar and Oldenburg 1984) indicates that the data constrains the *cumulative conductance* versus depth curve much more than the conductivity or resistivity versus depth. A consequence of this is that many layered models will closely fit one sounding provided they have similar cumulative conductance as a function of depth. However, as illustrated in this example, the depth to the top of a layer conductor can be well defined. The bases of both the surficial weathered material and the mineralized zone do not correspond well with the base of the modeled conductive layers. It should be noted that at late times (>40ms) the apparent resistivity plot exhibits behaviour that cannot be fitted by any layered earth model. Such behaviour is not uncommon and considerable research is being done on methods of recognizing and handling these effects. Their cause may include instrumental effects, static magnetic susceptibility and superparamagnetic effects, induced polarization responses, and simple inductive effects due to lateral variations in conductivity. As discussed by Spies and Eggers (1987), even over a purely layered earth, the limiting approximations used to transform voltage

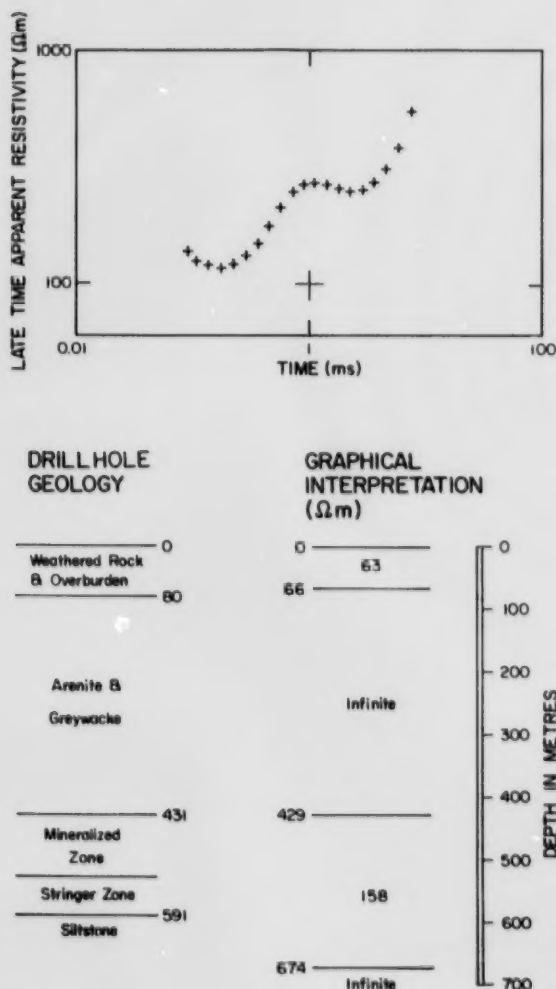


Figure 13.6. Graphical interpretation using type curves of TEM data presented as a late-time apparent resistivity over a reasonable well-layered site in Western Australia (from King and Peacock 1985).

data to apparent resistivity may not produce real apparent resistivities.

Figure 13.7 presents an example of the late time apparent resistivity presentation of data from South Australia (King and Peacock 1985) where EM was used to sound a deep, mineralized conductive feature. In this case data were collected using three different sizes of transmitter loop to improve the resolution of both shallow (using the small loop) and deep (using the large loop) responses. The data were inverted using non-linear least-squares algorithm (Anderson 1982). The inverted depth to the top of the good conductor interpreted to correspond to the massive hematite target, is considerably less accurate than the last example, because of the greater surficial conductance, and a moderately low resistivity section through the shales. Although the hematite zone is extensive, its horizontal extent is limited and must account for some error in the fitting process.

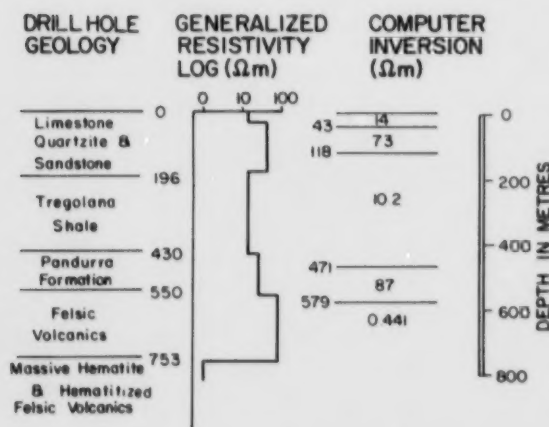
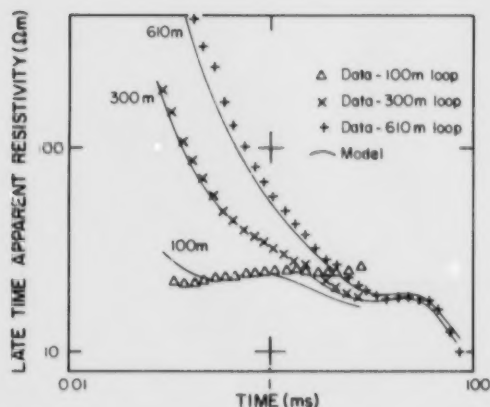


Figure 13.7. An example of graphical layered earth interpretation in a more complex area in South Australia (from King and Peacock 1985).

In methods such as seismic data processing, significant improvements in physical property imaging have long been achieved through spatial stacking (the Common Depth Point or Common Reflection Point stacking techniques) and data redundancy, expressed in terms of multifold coverage. Such techniques can, with care, be used to minimize the effects of very local structure and inhomogeneity on the stacked section, leading to better regional characterization (Dobrin 1976). Recent research in EM processing techniques (Macnae and Lamontagne 1987) has provided an empirical technique that, with step response data, allows for stacking of multifold data in an imaged depth domain. Figure 13.8 shows an example of three-fold UTEM data, where each receiver location has been measured from three different transmitter source locations. The response at each delay time has been plotted along profiles from each transmitter loop. After the measured data at each delay time and station has been transformed into an equivalent depth of current penetration, a weighted stack produces the simpler presentation of the data as a downward diffusion of the image of a ground current system as a function of time (Figure 13.9), plotted below each receiver station as profiles of image depth at each delay time. Using the EM diffusion equation, the data was then transformed to an imaged conductivity-depth section as shown in Plate 13.1 (see Colour Folio near back of book).

As an illustration of the depth capability of current systems in structural/regional investigations relevant to mineral exploration, crustal sounding in resistive terrain to depths over 15 km has been achieved using the UTEM system as part of project LITHOPROBE in Canada. Plate 13.2 shows the results of a three fold survey (Kurtz *et al.*, in preparation) over the Kapuskasing structural zone, believed to be the suture zone of an archaic overthrust. The solid line represents the location of a poor seismic reflector provisionally interpreted to be the expression of the zone at depth. Experiments using EM to map overthrust belts or regions of volcanic cover to maximum depths of one to three kilometres using controlled-source techniques in the exploration for petroleum are easily within the range of current instrumentation (Nekut 1987).

Difficult Environments:

Significant advances have occurred in our ability to infer the presence of conductors beneath variable near-surface conductivity. Figure 13.10 shows an example of how modeling and hence geological interpretation has advanced in recent years (Irvine and Staltari 1984). This example is included to demonstrate the interpretational advantages of more than one direction of primary field excitation, a point also demonstrated by Spies and Parker (1984). The geology as now known consists of a change in the near-surface conductance without any steeply conducting features. Nonetheless, a simple

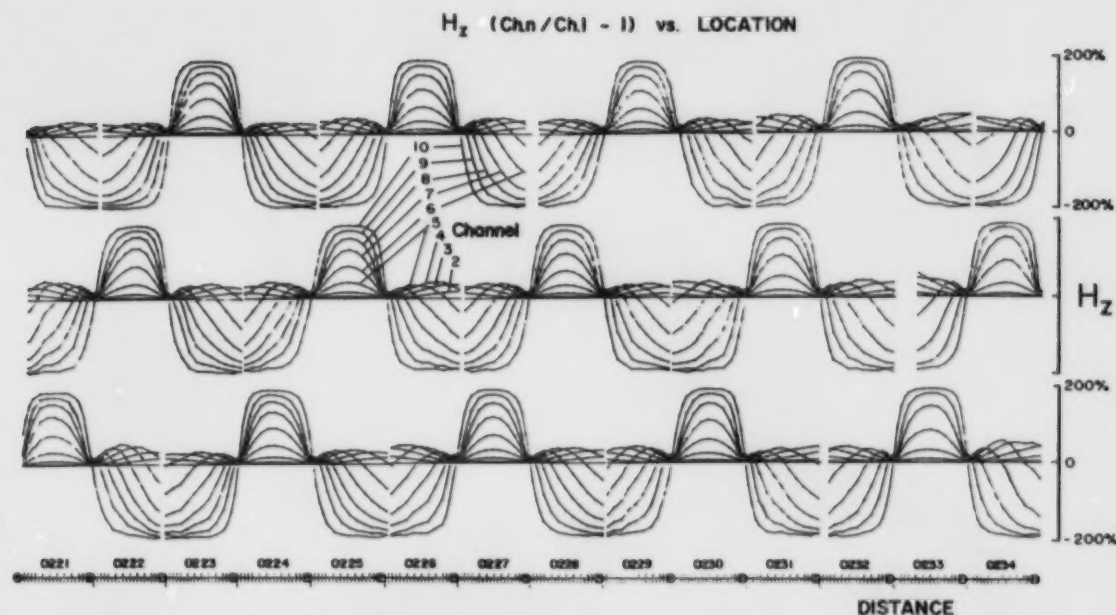


Figure 13.8. Three-fold UTEM data profiles over a sedimentary quasi-layered environment (from Macnae and Lamontagne 1987).

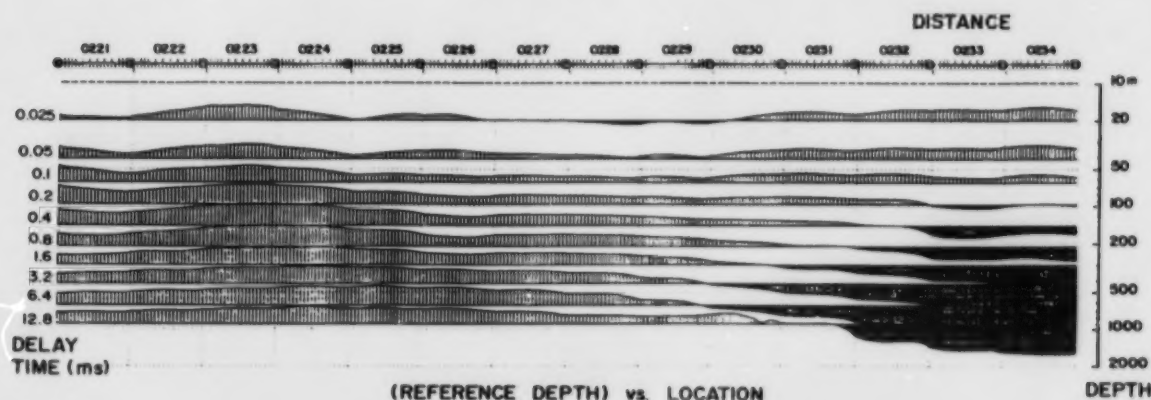


Figure 13.9. The data of Figure 13.8 transformed to imaged depth and then averaged over the three transmitter locations for each receiver site. Data was collected at 10 delay times per station (from Macnae and Lamontagne 1987).

crossover anomaly in the vertical component surveyed from Tx loop 1 was initially confused with the anomaly of a steeply dipping conductor due to the stationary location (in time) of the negative peak (Figure 13.11). After drilling failed to intersect a deep conductor, further work and analysis was performed. With the availability of recent scale modeling, the large positive response on the Tx 1 side of the crossover, together with a stationary negative is characteristic of a horizontal conductor under the transmitter loop terminating at the vertical line drawn over the data. Confirmation that this model is

correct is provided by the response from Tx loop 2 located on the other side of the feature; where a crossover response migrates away from the conductor edge.

Hellyer

The discovery of the Hellyer base-metal deposit in Tasmania is a fascinating example of the success of modern equipment and interpretation methods in detecting difficult targets. The challenge in this case lay in detecting a body whose cross section was very small compared to its depth of burial, located within

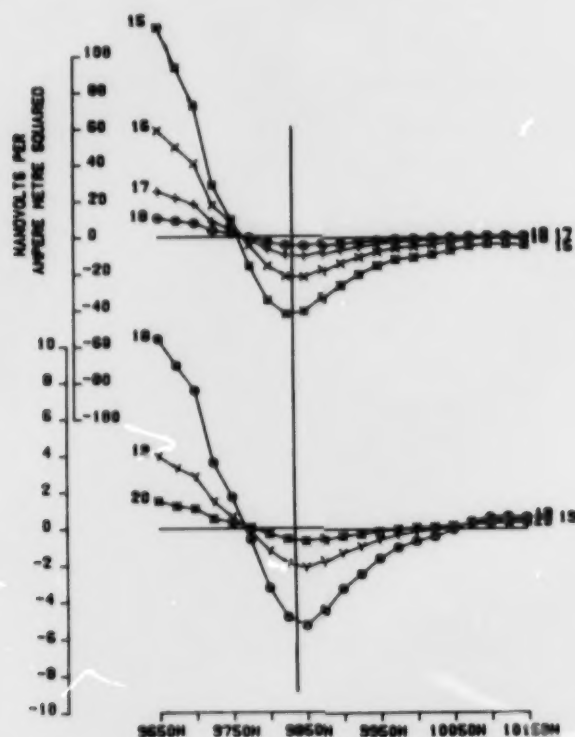


Figure 13.10. EM37 profiles from Queensland, Australia showing a late time negative peak response that decays without significant lateral migration (from Irvine and Staltari 1984).

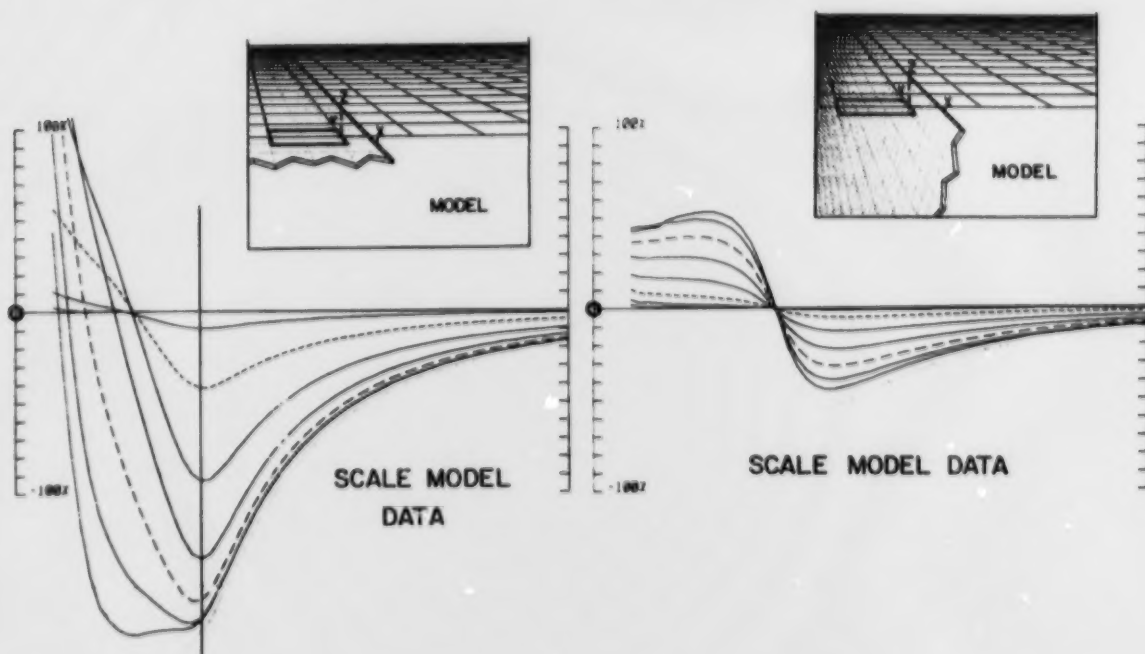


Figure 13.11. Scale model data showing the difference in response over a steeply and flatly dipping half-plane conductor (from Macnae 1985).

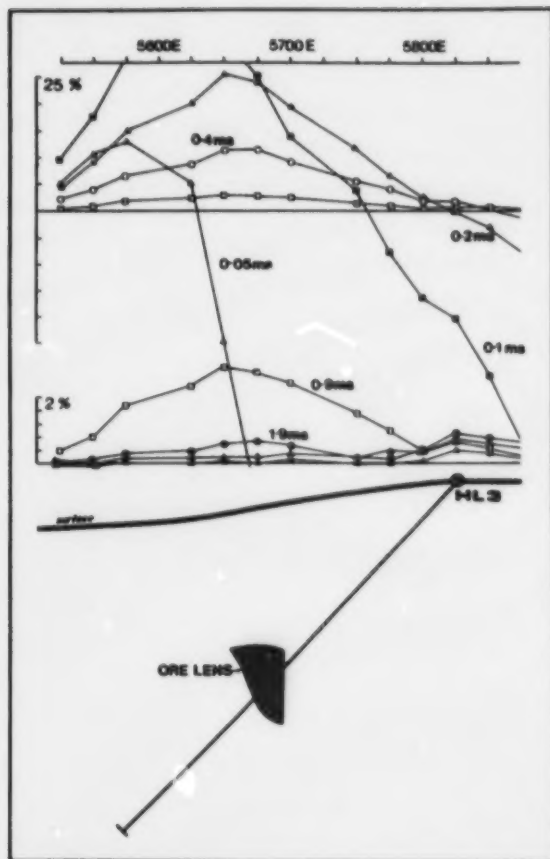


Figure 13.12. Surface UTEM data and discovery hole HL3 over the Hellyer base-metal deposit in Tasmania (from Eadie 1987).

a somewhat conductive host and where the surface survey lines were immediately adjacent to extensive, laterally varying conductive shales (Silic *et al.* 1985). Figure 13.12 shows one line of UTEM field data and the discovery hole HL3. As discussed in Eadie (1987), the response is a combination of a number of individual components, only a very small part of which at late times can be attributed to direct induction in the body (Figure 13.13).

CONCLUSIONS

Considerable progress has been made during the last decade in both EM instrumentation and interpretation. Research into improving methods of data acquisition, instrumentation, and interpretation for mineral exploration will no doubt show a significant increase should base-metal prices increase. Spin-offs from research into energy exploration, crustal sounding, and other applications of EM will undoubtedly lead to significant future improvements.

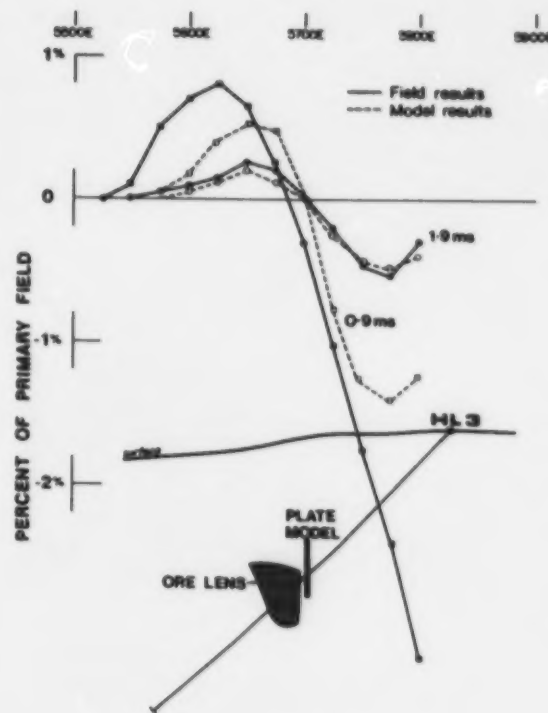


Figure 13.13. Utem data and fitted late delay time model for the Hellyer conductor on line 10400N. The increased amplitude in response at early delay times compared to the model is attributed to current gathering into the Hellyer conductor (from Eadie 1987).

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14. Electromagnetic Exploration from Boreholes

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ABSTRACT

Borehole electromagnetic techniques have become important prospecting tools for deep conductive targets in some exploration programs. They are, nevertheless, fraught with interpretation problems because we are often forced to deal with responses of the earth on a more intimate and detailed basis than in the counterpart surface applications. The objective of this paper is to illustrate the limits of interpretation methods at our disposal. Generally these limitations fall into the category of interpretation in conductive environments which are broadly defined here as conditions under which free-space, single-conductor models give inadequate answers. Conductive environments, therefore, include cases where: a) the host rock is conductive; b) other, discrete, geologic conductors generate an interfering response; c) the mine (or other artificial) structure, in proximity to which borehole EM surveys are being performed, is itself a large conductive framework.

We will deal primarily with the standard large-loop time-domain EM configuration, a reflection of the method's power and popularity. The discussion, organized according to the number of conductors and the complexity of the induced current regime, includes a succinct review of interpretation models, sign changes in transient EM responses, and a series of field examples selected from Australian and Canadian locales. The diversity of new experience and problem types which are coming to light is clear evidence of the steepness of the learning curve. Presently available interpretation aids based on computer and scale modeling are often useful, when carefully and cautiously applied, but still require a strong physical understanding on the part of the interpreter. Examples of promising innovations are: wideband three-component magnetic sensors, electric-field measurements, filament-inversion techniques which yield equivalent-current flow paths, and direct interpretation by modeling of the response of conductors in conductive earths.

INTRODUCTION

The application of electromagnetic (EM) methods in drillholes has, in recent years, become a viable tool in the exploration for conducting mineral deposits through advances in instrumentation, procedure, and interpretation. An increased understanding of

methods has been achieved both empirically, through extensive field work by many contractors and explorationists, and theoretically by analytical and scale-model studies. In addition to the utility of borehole EM, there remains a fascinating complexity to challenge both practitioners and researchers in the field. We are clearly on a steep part of the learning curve. The object of this paper is to describe the state-of-the-art, through an examination of that curve from the perspective of the geophysicist who, on the one hand must "get on with" the interpretation using facilities at hand, yet eagerly awaits new tools and findings.

There are other borehole EM methods, but this paper is concerned with the one referred to as large-loop EM (LLEM) illustrated in Figure 14.1, a reflection of the power and popularity of this configuration. The source of the magnetic field is a large (≥ 100 m) loop (Tx), usually placed (Crone 1986) in one or more locations near the collar of the drillhole, or above it, on surface, if the hole is situated in underground workings. The sensor, which in

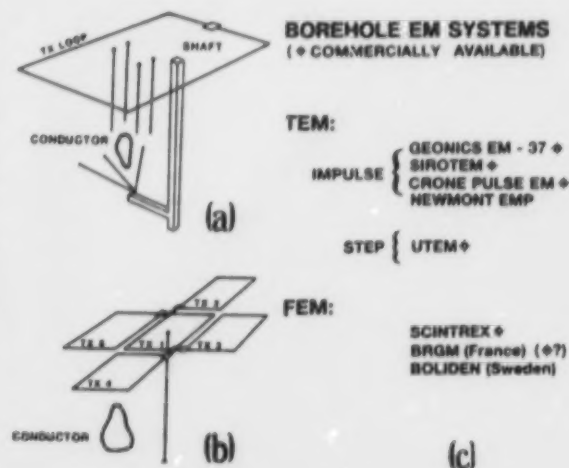


Figure 14.1. Borehole EM instrumentation. Commonly used layouts for the large-loop (LLEM) method: a) a single transmitter loop for surveying a collection of holes; b) multiple loops, deployed for surveying an isolated drillhole, to provide information on the direction (i.e. azimuthal location) of the target with respect to the hole; c) some LLEM borehole systems in existence in 1987/88. Both time-domain (TEM) and frequency-domain (FEM) systems are represented.

the conventional equipment is a single-component induction coil, co-axial with the drillhole, travels downward on a cable that serves as both mechanical and communications link between probe and receiver. Drillholes as long as 2 km can be surveyed with modern equipment, a list of which appears in Figure 14.1c. Time-domain (TEM) and frequency-domain (FEM) systems are included. Four of the systems are of the impulse type and known as pulse systems. While details of the waveform and sampling scheme are different, all of these interrupt the current in the transmitter in a cyclic manner thus producing a series of pulses. Any secondary fields induced in conductors in the vicinity by the magnetic-field interruption are then detected and sampled as a transient after the pulse, during what is known as the "off" time, with a set of windows or gates (see for example, Levy and McNeill 1986; Woods and Crone 1980; Dyck and West 1984; Boyd and Wiles 1984; Buselli and O'Neill 1977). Details of the step-response system may be found in West *et al.* (1984). It uses a triangular current waveform which then produces a series of step voltages in the receiver. The secondary field is measured, while the field is on, as a transient departure from the primary field. The FEM systems are continuous-wave (sinusoidal) methods which measure in-phase and quadrature components of the secondary field. An amplified discussion of the above system types, particularly with reference to the principles underlying the anomalies generated by each, may be found in Dyck (in press).

The above mentioned equipment has all been developed (or improved) in the last ten years. In the proceedings of Exploration'77, only two borehole EM examples were published (Seigel 1979; Crone

1979). Since then, many new technological developments have been incorporated and it is no accident that evolution of borehole methods has paralleled development of modern surface EM methods which use a large-loop transmitter. It is a credit to the builders that the equipment and the field data thus produced have reached a state of high reliability, such that borehole EM methods contribute regularly to the finding of conductive deposits (in Ontario and Québec alone, at least six recent discoveries have involved borehole EM, including the Aldermac deposit, an example to be shown below).

The state-of-the-art in interpretation methods is not nearly so easy to define. This paper is devoted, therefore, to an account of methods available and types of problems encountered, drawing mostly on recent published examples from Canada and Australia. We will concentrate throughout on TEM aspects.

CLASSIFICATION OF INTERPRETATION PROBLEMS

Figure 14.2 shows four categories on which our discussion of interpretation problems will focus. We have chosen, as the basis for this classification scheme, the same physical basis as used by Macnae and Staltari (1987) for their elucidation of sign changes encountered in TEM survey data. The rows of the classification matrix (Figure 14.2a) refer to the number of conductors in the problem; the column is determined by the complexity of the induced eddy current vortex in each. The categories are (Macnae and Staltari 1987):

1. SS Single conductor, single current vortex
2. SM Single conductor, multiple current vortices

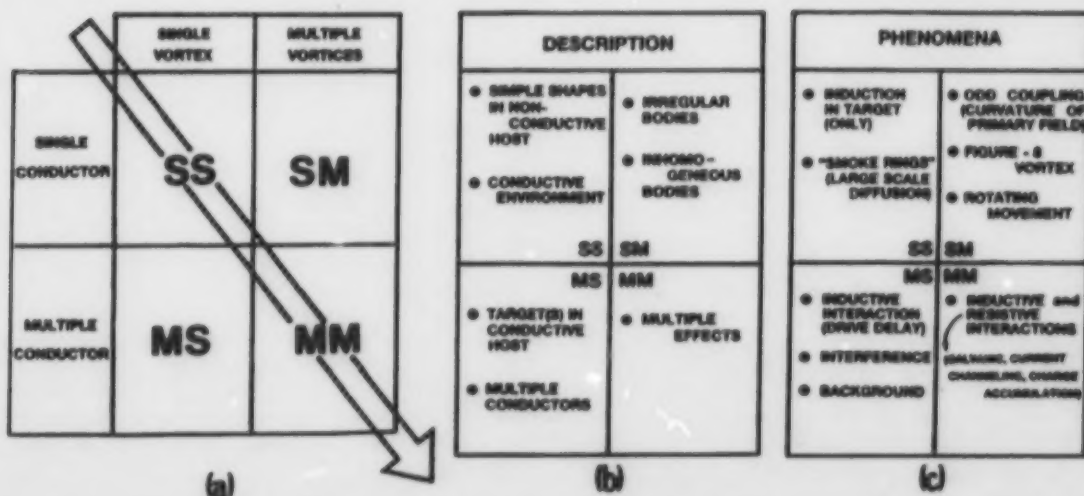


Figure 14.2. Classification scheme for interpretation of borehole EM anomalies: a) the physical basis for the four categories consists of the number of conductors in the problem, and the number of eddy currents (vortices) induced; b) A description of conductivity models which give rise to; c) the physical phenomena as referred to by a variety of terms.

3. MS Multiple conductors, single current vortex confined in each

4. MM Multiconductors, multiple current vortices in some/all, or transmitter current crossing conductor boundaries

It can be seen, with reference to Figures 14.2b and 14.2c, that the direction of the arrow in Figure 14.2a represents the direction of increasing complexity. The simplest cases (SS) are those in which there is a single target in a resistive host, or where there is no target but the host is itself conducting. The result is, respectively, that either simple free-space induction occurs (Dyck and West 1984), or that "smoke ring" diffusion (Nabighian 1979) can be used to describe the progression of the vortex away from the transmitter.

More complex are those cases (SM) where the target is situated in a resistive environment but is sufficiently irregular, either geometrically or in distribution of conductivity within, that induction in various parts of the body may be significantly different. This category has been somewhat enlarged to include situations wherein the eddy current changes drastically in orientation during the decay e.g. rotating moment (Dyck, in press).

MS cases include: a) a single target situated in a host which is sufficiently conducting to provide a shielding or "current blanking" effect, and b) multiple discrete conductors if the inductive interaction between them is significant. Also important on occasion is the effect of background response provided by neighbouring discrete conductors such as mine structure or powerline networks.

The final, and most complicated, category (MM) encompasses multiple effects, including inductive and resistive interactions which occur when a conductive body is embedded in a conductive host (for a more complete discussion of these multiple effects, see McNeill *et al.* 1984; West and Edwards 1985).

SIGN CHANGES

An understanding of sign changes in TEM response is critical to the successful interpretation of borehole data. In the most rudimentary consideration, we have the ability to determine whether or not the conductor has been intersected on the basis of the sign of the anomaly peak (Crone 1986). This ability may be jeopardized if other aspects affecting the sign of the transient, shown compiled in Figure 14.3, are not properly considered. The Macnae and Staltari (1987) treatment of these was stimulated by frustration on the part of interpreters in dealing with the myriads of sign changes observed in Australian cases. Figure 14.3b distinguishes between a sign change as a function of space (generally termed crossover) and a sign reversal in the transient at a particular point in space. If the latter occurs at the

same time for all parts of the anomaly, the anomaly is itself seen to reverse. A combination of sign reversal and crossover results in a migrating crossover.

Figure 14.3c illustrates the effect of current blanking on step (secondary field represented by H^s) and impulse (represented by dH^s/dt) responses. In a resistive earth, the response of a conductor to a step change in primary field, H^p , is a step jump followed by a decaying transient, while the impulse response is a short pulse followed by a transient of opposite sign. The sign reversal occurs too early to be sampled so it goes undetected in resistive terranes. However a conductive earth produces a smoothing/delaying effect on the field that the target "sees" (drive delay). This in turn produces a time-smeared transient which, in step response, is seen as an increase followed by a decline, all of the same polarity. The impulse response is seen, however, as a transient which reverses sign before decaying to zero. It follows that, because the (im)pulse response is, in principle, the time derivative of the step response, there is always one more sign reversal in the pulse response as compared to the equivalent step response, should there be reversal for reasons in addition to drive delay. This fact is noted in the MS category of Figure 14.3a. Sign reversals are also caused by migration of the "smoke ring" so as to produce a mutual change in coupling with the receiver, and by migration of an eddy current confined to a target past an intersecting borehole.

Figure 14.3d serves as reminder of further complications which arise from current channeling and/or interaction with other conductors (H^E and H^p , respectively) as the signs of these contributions to the measured response is determined by location of the target. Induced polarization may also be important. The reader is referred to Macnae and Staltari (1987) for full explanations of points that we have summarized here.

INTERPRETATION

The models and interpretation aids to be discussed in this section provide, of course, much of the basis for the above classification system and summary of sign changes. Figure 14.4 shows the main sources of this information. In the SS category, simple models, plate and sphere in free-space are the mainstay. A comprehensive plate-model suite by Woods (1975) includes both intersection and non-intersection cases. These are supplemented with sets of plate and sphere models, including conductive overburden, by Parums (1984) and Kneebone (1985). Computer implementations of plate and sphere models (e.g. Dyck *et al.* 1980; Blair 1983) provide the flexibility required to deal with arbitrary geometries encountered in drillhole surveying. A simple, but indispensable, tool is the Macnae (1980) Atlas of primary fields for rectangular transmitter loops of various shapes. Figure 14.5 illustrates application of a primary field diagram to determine the transmitter cou-

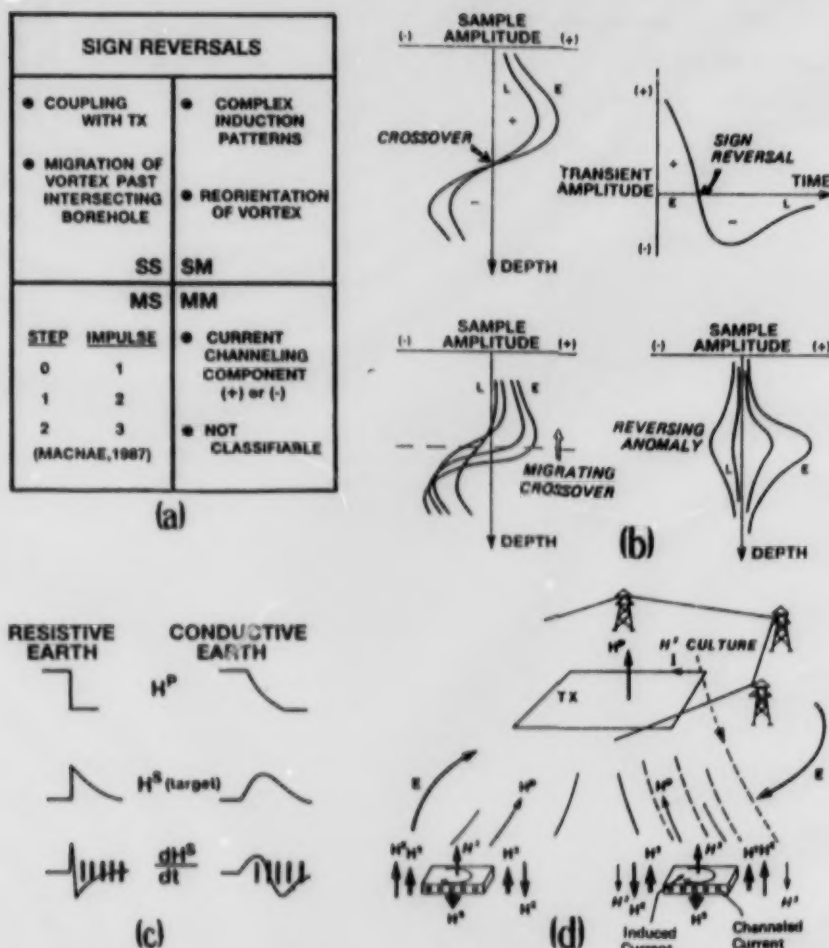


Figure 14.3. Sign changes in borehole TEM responses: a) classified according to Macnae and Staltari (1987); b) definition of terms; c) effect of drive-delay on step response and pulse EM systems (secondary field H^s in response to a step change in primary field H^p is the system-function equivalent to the principle of the UTEM system listed in Figure 14.1c; West et al. 1984); d) some possible vector contributions to an observed anomaly. The components of a borehole TEM response can be combined in many ways, depending on the physical and geometric characteristics of the problem.

pling that a plate conductor would be subject to for two different locations. Thomas (1987) shows how simple anomaly shapes from non-intersected plates may be classified and qualitatively interpreted on a nomogram (using a current-filament model).

Migration of eddy currents within isolated targets, and their borehole manifestations have been discussed extensively by Dyck and West (1984). An interpretation trick applicable to intersected conductors (Macnae and Lamontagne 1986) is illustrated in Figure 14.6. If the borehole fortuitously intersects (in a non-perpendicular orientation) a migrating sheet of current flowing in a conductor, one or more of the anomaly traces will exhibit a tangential discontinuity (Grant and West 1965). The sense of the discontinuity superimposed on the main anomaly will

be determined by whether the conductor has been intersected at its lower or upper edge, effectively indicating in which direction the bulk of the target lies if its dip is known.

In Figure 14.4, the sphere model has also been included in the SM category. It is felt (Dyck and West 1984) that sphere-like effects can be helpful to explain, or at least be indicative of, non-tabular features of a target, and is therefore an under-utilized model, especially when implemented in computer form readily adaptable to different situations.

Other studies are more of an heuristic nature. These include borehole observations of half-space effects studied by Levy and McNeill (1986), scale-model studies by Dyck (1981) of thick blocks and multiple plates in free-space (see Figure 14.7 for an

INTERPRETATION	
• WOODS' (1975) MODELS • PLATE and SPHERE • AMPLITUDE, SHAPE, MIGRATION, TANGENTIAL DISCONTINUITY • SVETOV'S RULE • MACNAE'S ATLAS • SMOKE RINGS • RECEDING IMAGE	• A FEW SCALE MODELS (e.g. DYCK, 1981) • SPHERE
SS	SM
MS	MM
• LEVY and McNEILL (1987) • SCALE MODELS (DYCK, 1981)	• 2 - D EATON and HOHMANN (1984) • 3 - D WEST and WARD

Figure 14.4. Facilities for interpretation of borehole TEM data. Not only are there more aids available for the SS category, but they have flexibility to accommodate a greater variety of geometries.

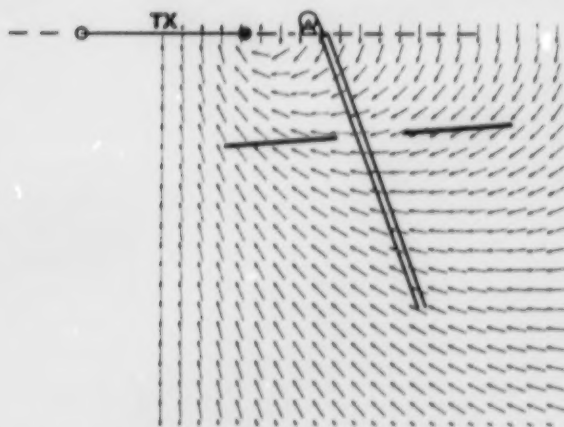


Figure 14.5. An example from Macnae's (1980) Atlas of Primary Fields, showing reversal in coupling between transmitter and a thin plate on either side of the drillhole. Considerations of this kind are helpful in planning multiple-transmitter surveys and in constraining the location of a target during interpretation.

example of the rotating moment effect caused by major re-orientation of the eddy current during its decay), and the numerical modeling of 2- and 3-D cases provided by Eaton and Hohmann (1984) and West and Ward (in press), respectively. The latter, an example of which is shown in Figure 14.8, is

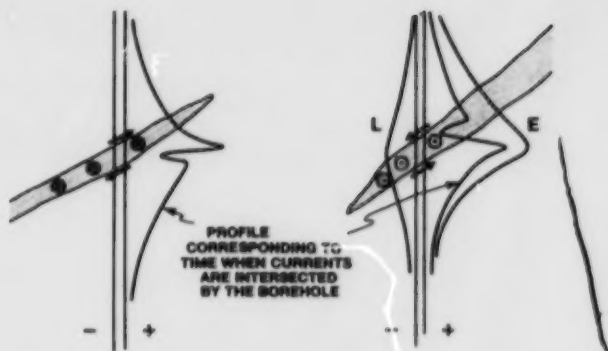


Figure 14.6. Interpretation of intersected conductors: a tangential discontinuity of the secondary field parallel to the face of the target can be detected by a co-axial coil as a component, provided that the borehole intersects the eddy currents at an angle. This information, together with the dip, is indicative of the location of the res: of the conductor.

based on the algorithm of San Filippo and Hohmann (1985). Of course, the concept of "smoke rings" (Nabighian 1979) and the moving picture film produced by Oristaglio (1983) (see Oristaglio and Hohmann 1984) to show subsurface fields around an imbedded target have been of major assistance in visualization of inductive behaviour in a conducting half-space.

EXAMPLES

Two recent workshops on borehole geophysical methods, one in Australia and one in Canada, are the source of the bulk of published cases, as documented in Figure 14.9. The distribution within the four categories (predominantly SS) is indicative of the proportion of cases which are reasonably well understood. The reader must certainly examine the published material directly to become better acquainted with the capabilities of borehole EM. We have selected several to present here to demonstrate certain key points.

ALDERMAC

This is a current base-metal project in the Rouyn/Noranda in northwestern Québec. Crone pulse EM data from one of the drillholes (R. Pineault, SAGAX Limited, Montréal, personal communication, 1987) and a geological schematic (information supplied by G. Archibald, Nuinsco Resources Limited, Toronto, personal communication, 1987) are shown in Figure 14.10. The EM data are interesting for two reasons: a) the transmitter loops couple with the conductor from two different directions, thus producing mirror-image anomalies below about 355 m, characteristic of a thin tabular body (SS category). This was the basis for interpretation of sulphides lying further along strike and subsequently

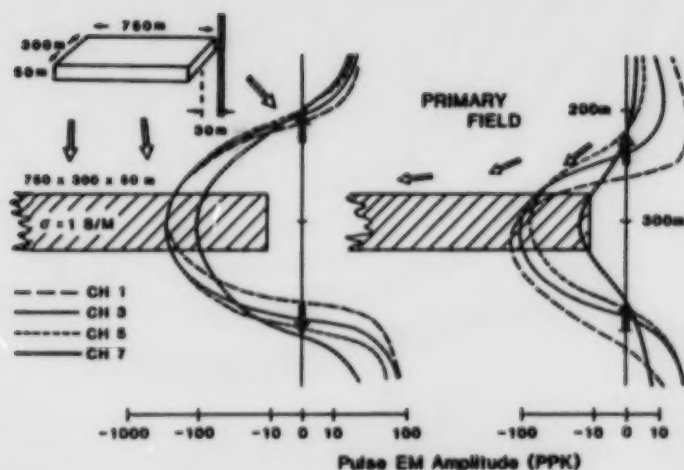


Figure 14.7. Simulation response of a thick, tabular body to a Crone pulse EM system for two different primary fields shown by open arrows. The crossover migration (closed arrows) and peak migration, which occur when the primary field intersects the edge face of a body, are indicative of re-orientation of the eddy current during decay (rotating secondary moment) (from Dyck 1981).

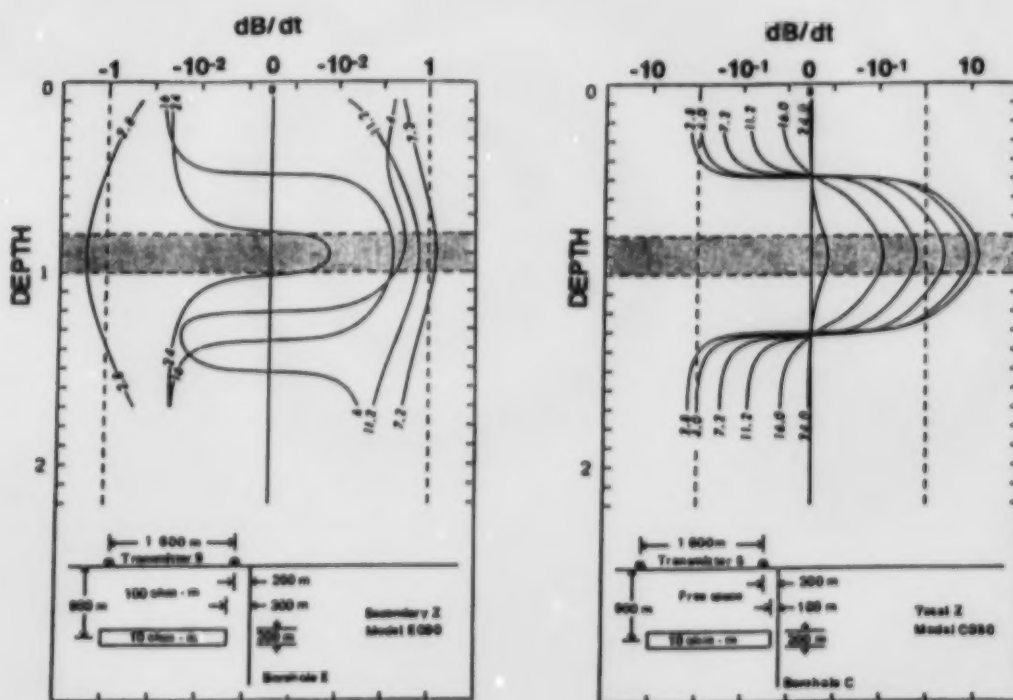


Figure 14.8. Impulse response (axial component of dB/dt) of a 3-D, square body (10 ohm-m) lying beneath a square transmitter loop (at a depth of 900 m). The delay time for each profile is labelled (ms) and the depth extent of the target is shaded: a) free-space response; b) target imbedded in 100 ohm-m half-space (only secondary fields caused by presence of body are plotted, i.e. response of half-space is not included). Note that the difference in response is primarily due to a half-space-altered vortex within the body. Had the target lain on the opposite side of the borehole, the response would have been dominated by current channeling because of decreased magnetic-field coupling and increased electric-field coupling between transmitter and target.

CASES			
♦ AUSTRALIAN WORKSHOP (ASEG)		□ CANADIAN WORKSHOP (KEGS / GSC)	
BOYD & WILES (1984)		♦ LANE (1987)	
□ CRONE (1986)		♦ EADIE (1987)	
♦ MACNAE & STALTARI (1987)		— ALDERMAC	
♦ COGGON & CLARKE (1987)		— TRILLABELLE	
♦ EADIE (1987)			
□ MACNAE & LAMONTAGNE (1986)			
□ REED (1986)			
□ BONIWELL (1986)			
DYCK & WEST (1984)			
	SS	SM	
♦ BISHOP et al	MS	MM	
♦ MACNAE & STALTARI		♦ IRVINE (1987)	
♦ ASTEN et al		♦ LANE (1987)	
♦ COGGON & CLARKE			
— RUTTAN			
— FOX			
DYCK & WEST (1984)			

Figure 14.9. A classification of borehole EM cases. Two workshops, sponsored by the Australian Society of Exploration Geophysicists and Canadian Exploration Geophysics Society/Geological Survey of Canada, respectively, are the main source of material. Unpublished examples are listed by site name alone (see text).

intersected; b) the anomalies above 355 m are significantly different from each other and from what could be caused by a simple body. This difference is the reason for classifying the response as SM in Figure 14.9, a speculation, on our part, that the causative body is considerably more irregular than is presently known. These latter enigmatic aspects of the anomaly is of the type that will form the basis for detailed modeling research.

HELLYER

The Hellyer prospect is a base-metal deposit in Tasmania. The EM-37 results shown in Figure 14.11 are taken from an oral presentation further reported by Eadie (1987), in which comparison tests of several different systems, both borehole and surface were discussed. The fixed (at 300 m) character of the crossover produced by LP1 is symptomatic of a conductor oriented with its broadest dimensions perpendicular to the inducing field, resulting in a vortex whose orientation changes little with delay time. The crossover produced by LP2 migrates in excess of 50 m down the hole, indicative of a vortex which is initially oriented perpendicular to the primary field, but then rotates, as it decays, (rotating moment effect) until it is aligned parallel to the broadest dimensions of the target.

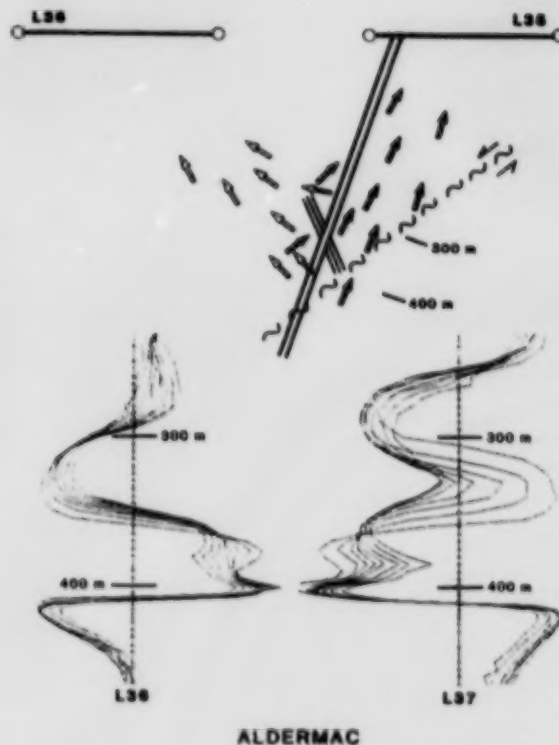


Figure 14.10. Drillhole in the Aldermac project surveyed with the Crone pulse EM system and two transmitter loops. The open and closed arrows represent the primary fields of transmitters L36 and L37, respectively. The sulphides shown projected on to the section as dipping at about 60 degrees towards Tx L35 were intersected further along strike on the basis of the borehole EM data.

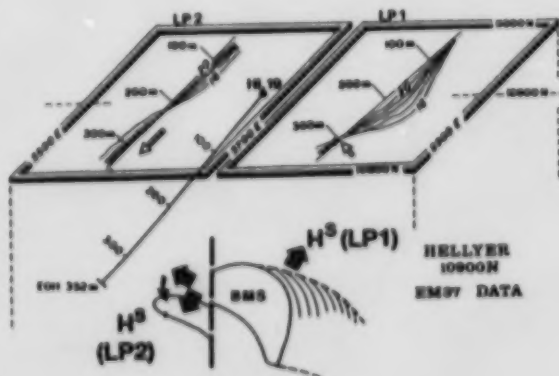


Figure 14.11. EM data illustrating the rotating moment effect. The open arrows on the profiles signify the behaviour of the crossover; the closed stubby arrows below represent the secondary field "moment" which changes direction for LP2 but remains fixed for LP1 (Eadie, 1985).

RENISON BELL

An example of SIROTEM data is shown in Figure 14.12. Renison Bell is a large tin mine in Tasmania, in which downhole EM surveys were employed in efforts to find more ore around and below the workings. The host rocks are thick, conformable successions of shales, quartzites, argillites, carbonates, conglomerates, and pyroclastics. The ore occurs as cassiterite-bearing pyrrhotite within stratabound deposits (replacement of dolomites) and as faultbound mineralization (Bishop *et al.* 1987). The sulphides are generally massive, highly conductive, and as they form a rather complex network, there is ample opportunity for inductive interaction between various bodies. It is not possible to enter into the intricacies of the interpretation here, but the anomaly at 540 m is interesting for its double sign reversal, one at 2 ms delay, the second at 40 ms. The earlier reversal is thought to be the result of shielding by shallower conductors, and the later one by contraction of currents past the borehole. The late-time anomaly was simulated with a rectangular filament model and it was suggested by Bishop *et al.* (in press) that the conductor is of sufficient size to warrant further investigation.

RUTTAN

Ruttan is a base-metal mine in northern Manitoba, Canada in which pulse EM surveys were evaluated for further exploration for the highly conducting copper-bearing massive-sulphide lenses. The data shown in Figure 14.13 are certainly indicative of the multiplicity of conductors in the West Anomaly area, where the conductors appear to be abruptly termi-

nated by crosscutting granites (M. Patterson, Sheritt-Gordon Mines, personal communication, 1985). The anomalies below 250 m correlate with intersected sulphides, shown as an Fe histogram on the geologic perspective diagram. The anomaly D2, interpreted qualitatively as a conductor lying above the hole, was subsequently drilled and found to be caused by non-economic sulphides. The data are interesting for the strong background, on top of which the local anomalies ride, thought to be caused by a network of conductive mine structure and mineralized horizons. Furthermore, the local anomalies do not change sign as expected from coupling considerations for each of the transmitter loops used, and from knowing the preferred orientation of the conductors by geologic observation. This again is thought to be a manifestation of the secondary-field background, which, at Ruttan, is strong enough to control the field which impinges on the targets at depth (Dyck 1985). Dyck and West (1984) presented a Sudbury basin example of target/powerline anomaly interference (simpler than the above) in which the inductive interaction was documented by computer model study.

It is worth noting that logarithmic display of amplitudes, such as in Figure 14.13, is convenient for dynamic compression of widely varying data but also renders impossible the comparison of anomaly amplitudes.

THALANGA

The set of data in Figure 14.14, from the Thalanga deposit, Queensland, Australia, provides an example of unexplained sign reversals (Irvine 1987). The mineralization comprises stratiform bodies of zinc, lead, and copper volcanogenic massive sulphides.

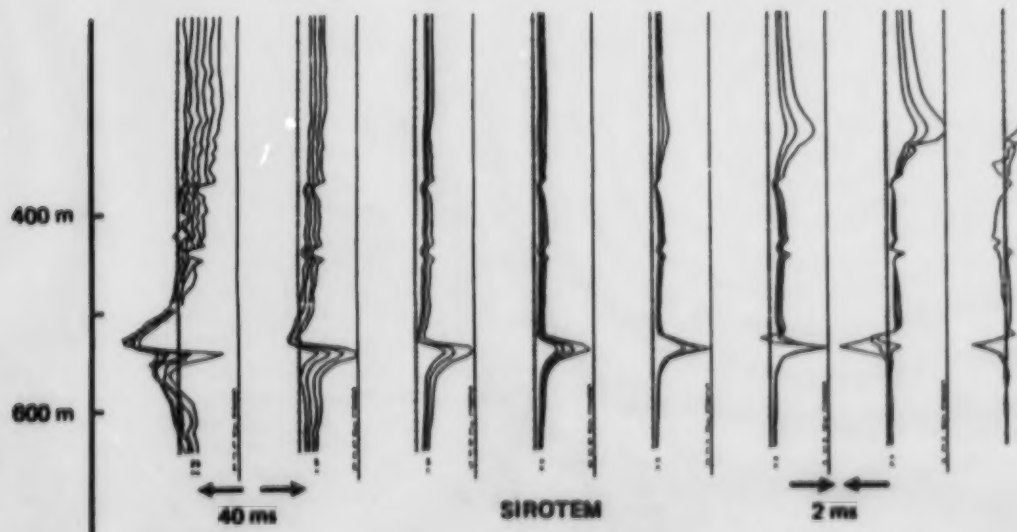


Figure 14.12. Borehole EM data demonstrating an anomaly with double sign reversal. The sequence of profiles ranges from early to late time, top to bottom, respectively, displayed with increasing gain (from Bishop *et al.* 1987).

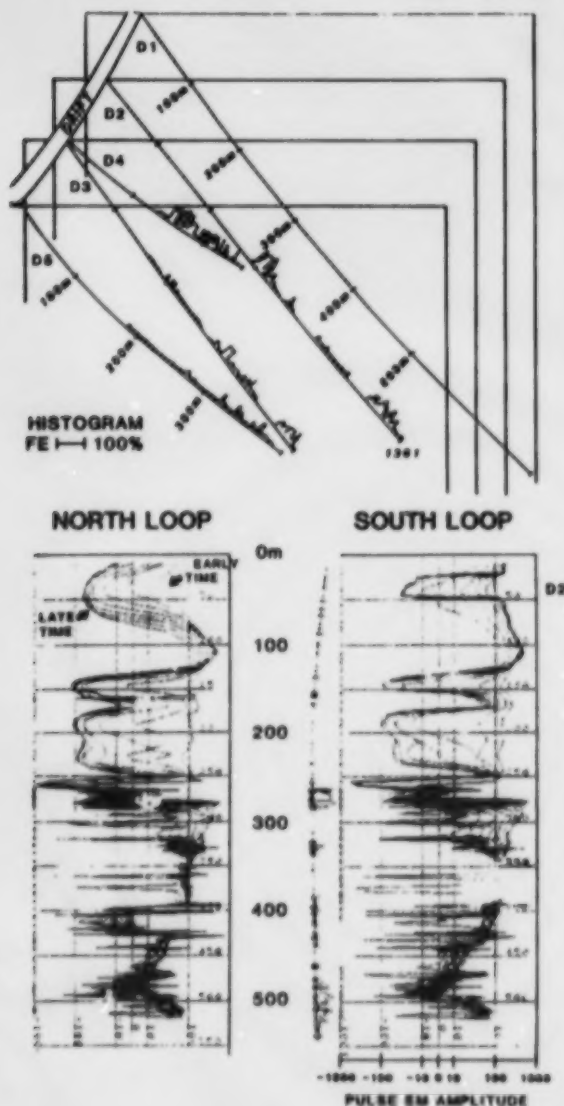


Figure 14.13. Crone pulse EM data from the Rutan Mine, Manitoba. The large-amplitude anomalies superimposed on a strong background response of the mine structure, and independent of transmitter excitation, implies significant inductive interaction between conductors.

The host rock comprises a relatively conducting overburden and a weakly conducting bedrock. Several effects were illustrated by Irvine, including a sign-reversal anomaly which he attributes to drive delay or to current channeling (actually, dominance by current channeling effects at early delay versus inductive effects at late times), either of which would explain the observed sense of anomaly reversal. The author points out that this ambiguity exists only for pulse systems and could be resolved by a step-re-

sponse system which (see above) produces a sign reversal for current channeling but not for drive delay.

The example of DDH 33 in Figure 14.14, however, cannot be explained in the same way. For LP1 the dominant peak at 400 m is negative at early times and positive at late times and vice versa for LP2 on the other side of the interpreted conductor. These anomalies are opposite to that expected from current channeling and induction, assuming that these will dominate at early and late times, respectively (Irvine 1987). The author, after speculating on several other possibilities including complex interaction between different parts of the target or dispersive effects (Smith and West 1986), concluded that further research was necessary to provide a conclusive explanation.

STATE-OF-THE-ART

Figure 14.15 summarizes the present state of borehole EM methods and some predictions on how they will advance. The state-of-the-art cannot be defined sharply but rather can be described by three zones which are superimposed on the classification matrix in Figure 14.15a. The first zone (upper left) corresponds to problems that can be handled in a reasonably routine manner. The information required by the explorationist can usually be extracted, although azimuthal location of the target sometimes remains a problem. The second (transition) zone contains problems that can often be understood through sound physical reasoning and heuristic model results, but for which there are neither routine solutions nor readily applicable modeling tools. Situations falling into the third zone (lower right) prove frustrating to the interpreter and provide little or no clarification of the exploration picture. It may even be impossible to determine which part of the downhole profile is anomalous, thus failing to identify the target or its depth. The difficult zone could reasonably include cases where the method is pushed beyond its usual limits by a desire for more precise information, for example, to guide development drilling of a target.

Figure 14.15b lists models that we feel are required for further understanding and especially for routine application. A conductive ellipsoid in free-space would fill the gap between plate and sphere models in terms of the constraint that the model imposes on the eddy currents (see Dyck and West 1984). Inhomogeneous models (e.g. more conductive core) and irregularly shaped bodies are necessary because there are many details of borehole EM responses which we do not as yet comprehend (e.g. subtle migration characteristics). It is important that these and any new models for the MM category be fast and flexible for routine application and custom-tailoring to a particular problem.

New developments are tabulated in Figure 14.15c. Filament inversion, which is Marquardt in-



Figure 14.14. SIROTEM example from Thalange, Queensland (Irvine 1987). The anomaly at 400 m, which coincides with a known massive-sulphide body above the hole, has unexplained behaviour with respect to current channelling and simple induction.

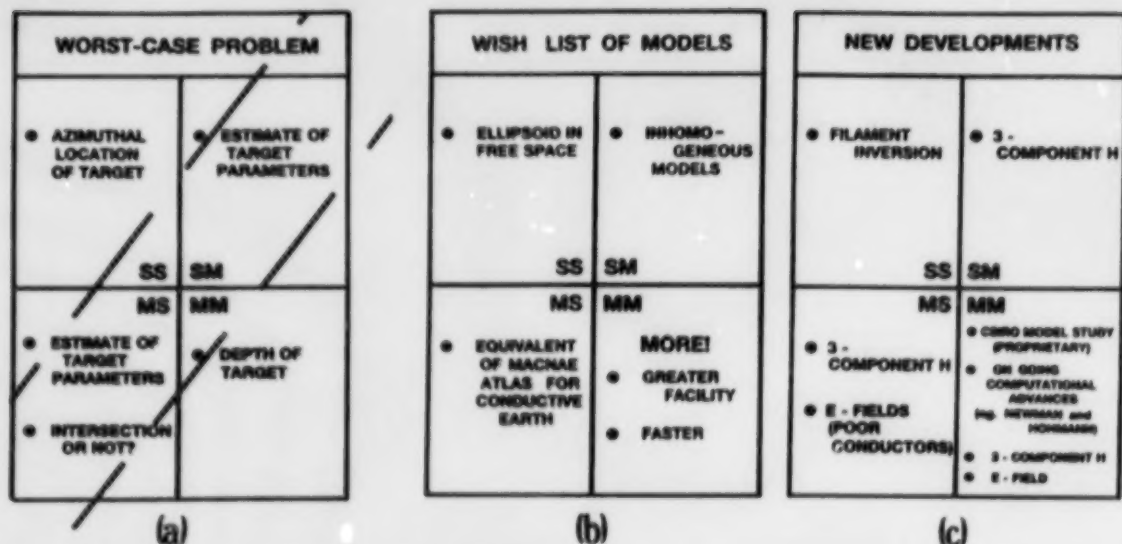


Figure 14.15. State-of-the-art in borehole EM methods: a) Worst-case problem for each category, with gradational state-of-the-art superimposed (grading from routine, to difficult, to very difficult problems from upper left to lower right); b) a list of desirable models; c) in-progress developments to advance the power of the method.

version based on rectangular or circular filament models (described by Barnett 1984; for borehole applications see Boyd and Wiles 1984; Taylor 1985; Fullagar 1987; Duncan and Cull, in press), is useful for defining targets as equivalent-current paths, especially for isolated conductors in free-space conditions, such as the late-time stage of decay. Figure 14.16 shows an example from the Lessard deposit, Québec, of successful application of this technique. Other interpretational advances expected to become available are a comprehensive tank-modeling study, an example of which is shown in Figure 14.17 (G. Buselli and S.K. Lee, CSIRO, personal communication, 1987) and ongoing numerical studies (e.g. Newman *et al.* 1986). Computer modeling of the 3-D EM problem is proving expensive in terms of machine resources. A supplementary, cheaper ap-

proach yielding insights into the physics of a restricted class of models is to use the parametric method of West and Edwards (1985) to compute separate half-space galvanic and inductive responses for a conducting disc target in a conducting half-space. This is an on-going project by one of us (MWA) and will be described elsewhere.

As compared to surface methods, borehole EM problems have more degrees of freedom and less information with which to work. One way to collect more data is the fixed-receiver method proposed by Coggon and Clarke (1987). The receiver is stationed at a fixed depth in the hole while measurements are made with the transmitter at several points on the surface. This approach, which is clearly labour-intensive, could be used to provide complementary information to the standard mode of operation, thus helping to constrain the location of the conductor.

The alternative is instrumentation-intensive: to measure additional parameters with the standard mobile-receiver configuration. Three-component magnetic-field measurement is somewhat of a panacea in that all four categories of problem would benefit, particularly in terms of conductor location (see Dyck 1981; Dyck and West 1982 for a modeling study). Operating systems have been developed by various workers (Kuckes *et al.* 1981; B. Krause, INCO, Sudbury, personal communication, 1982; Pantze *et al.* 1986; Cull and Cobcroft 1986; Lee 1986).

Development of a transverse wide-band magnetic sensor is, of course, made difficult by the constraints of slim drillholes. The transverse sensor constructed by Lee (1986) and shown in Figure 14.18,

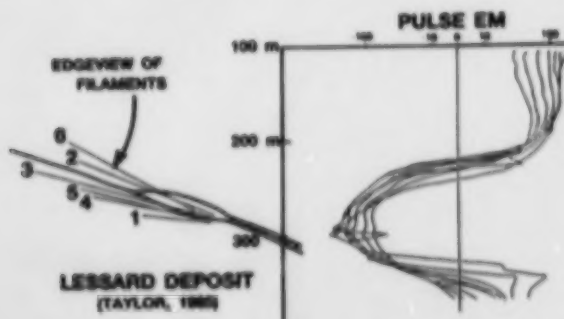


Figure 14.16. An example of interpretation of pulse EM data by filament inversion.

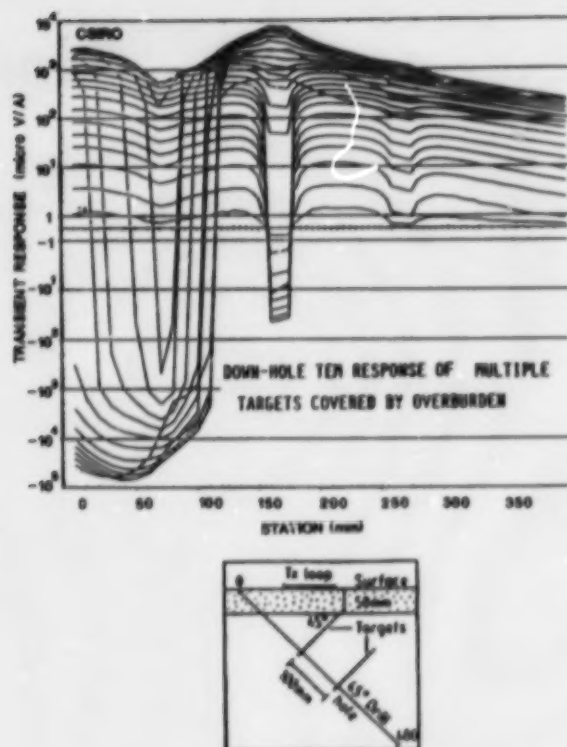


Figure 14.17. An example of a scale-model SIROTEM response (G. Buselli and S.K. Lee, CSIRO, Australia, personal communication, 1987). The scaled equivalent parameters are: overburden is 100 m thick, conductance 12 S; targets are each 47 S, separated by 200 m. Note: that the response of the upper target strongly shields that of the lower; response of the overburden gives strong negatives at early times and shallow depths, and also changes sign of target response at early time.

has an effective area of 60 m², a bandwidth of 5 kHz, and fits into an A-size (47 mm) drillhole. Figure 14.19 shows results of a test survey using the 3-component probe with a pulse EM system. The field data shows that the performance achieved with the transverse sensors is comparable to the conventional-design longitudinal sensor, and to the commercial version (see Dyck and West 1984, for field data from the same site). An excellent model fit was obtained using a thin rectangular plate situated to the south of the drillhole.

Electric-field measurements have been shown, by Hayles and Dyck (in press) using very low frequency (VLF) radio signals, to be useful for detecting and analysing poor quality conductors. Measurement of electric fields produced by a LLEM system would likewise extend the range of conductors to which the method is sensitive, in addition to resolving ambiguities associated with current channeling, simple induction, and induced polarization. Downhole magnetometric resistivity (e.g. Nabighian

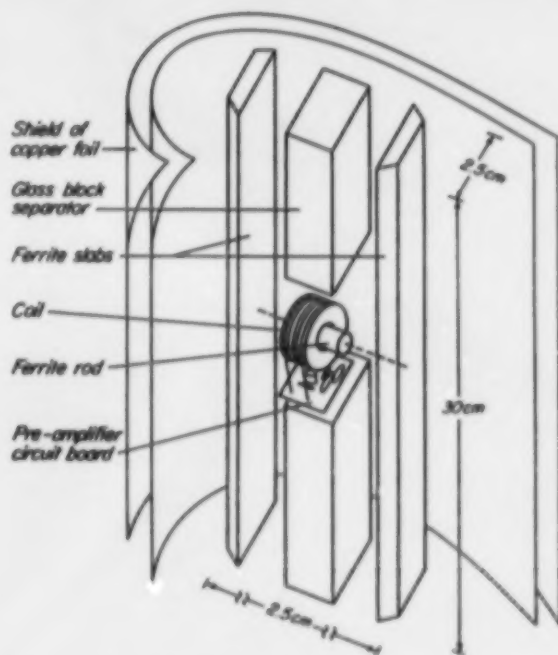


Figure 14.18. Schematic of a recent wide-band, transverse-component sensor for use in a 3-component, borehole magnetic TEM probe (Lee 1986).

et al. 1984), while not a LLEM method because a grounded dipole is the source, would provide a useful complement to standard surveys in that the current-channeling component is detected directly, thus providing directional information (Asten 1988).

Borehole EM surveys offer a unique opportunity to study the electromagnetic response of the earth in considerably greater detail than was previously possible with surface methods alone. Presently available interpretation aids based on computer and scale modeling are often adequate, producing many results useful in the exploration process, when carefully and cautiously applied. A strong physical understanding on the part of the interpreter is still required, however. Developments in progress will ensure that the accelerated pace of learning that has occurred over the last ten years will continue unabated for the next decade, as we find new ways to use and display the data.

ACKNOWLEDGMENTS

The present state-of-the-art is the result of the efforts of many. We would particularly like to acknowledge the contribution of the users of borehole EM for their willingness to risk engaging a new method. May they continue to do so. We would also like to thank George Archibald of NUINSCO Resources Limited, Toronto and Rejean Pineault, then

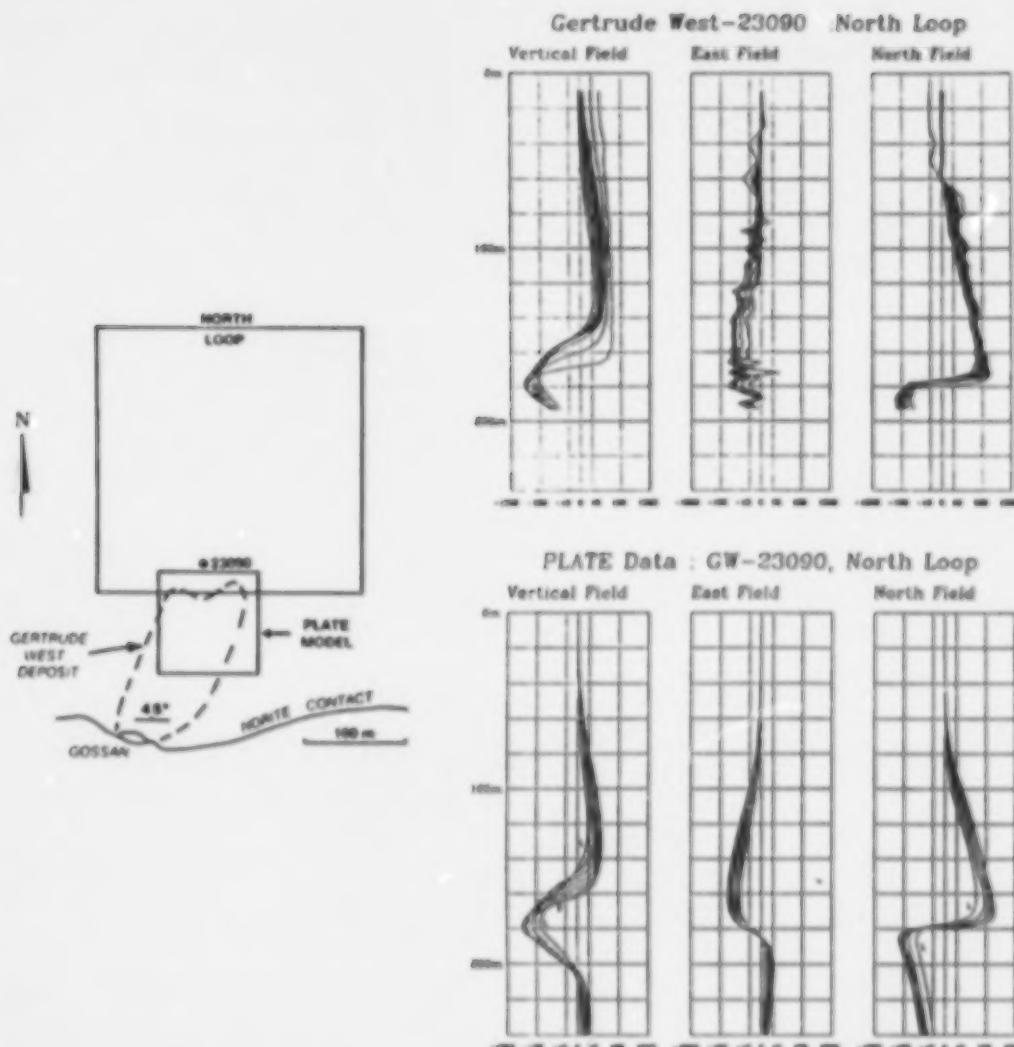


Figure 14.19. A comparison of field and model data for a 3-component drillhole EM survey at the Gertrude West deposit, Sudbury. The survey was carried out using Lee's (1986) probe together with a Crows pulse EM system, in cooperation with the Geological Survey of Canada.

of SAGAX Limited, Montréal, for permission to present the Aldermac data at a very early stage of exploration. Thanks also to Carol Luce who drafted the figures.

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15. Advances in Geological Mapping with Airborne Electromagnetic Systems

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ABSTRACT

Modern airborne electromagnetic (AEM) systems can measure the response of geological conductors in a wide conductivity band. In mineral exploration, particularly for gold, not only are highly conductive massive sulphides of interest, but also formational conductors are of interest. Most Canadian geophysicists will recognize anomalies due to graphitic conductors, but few are familiar with saprolite which is formed by *in situ* chemical weathering of rocks. The weathering mechanism is described in the paper and variations in electrical properties of the weathered layer are demonstrated on examples from Burundi, Brazil, and other countries. Because the conductivity of saprolite varies according to the underlying lithology, geophysicists can identify mafic and felsic volcanic units, intrusive bodies, and some sedimentary rocks from conductivity patterns on AEM maps.

Since the mid 1970s, AEM methods have been successfully used for geological mapping. Old and improved geological maps are compared for one area in the Itapicuru Greenstone Belt, Bahia, Brazil.

Conductivity maps correlate better with lithological units than magnetic maps. AEM responses due to saprolite and graphitic sediments have frequently been encountered in the Labrador Trough, Québec. Correlations are made in the paper between AEM, magnetic, and geological maps from the Thompson Lake area (sheet Lac Bacchus, Québec).

A new application for AEM methods is mapping of Quaternary sediments. Test surveys in northern Ontario have demonstrated that at least three sediment types (sand and gravel, tills, clays) can be identified on the basis of their distinct conductivity. Buried valleys have been successfully located using AEM methods, and in most instances, the estimates of sediment thickness based on EM data were reasonably accurate. A conductivity map is shown for the Val Gagné test site. Colour bar maps of apparent conductivity, depth to bedrock, and VLF response are given for one segment of the Kapuskasing transect along with the results of ground horizontal-loop EM surveys.

INTRODUCTION

The first functioning airborne electromagnetic (AEM) system was developed in the early 1950s in Canada to be used as a tool of prospecting for mas-

sive sulphide bodies. The first discovery of an economic orebody using such systems was made in 1954, when the Heath Steele lead-zinc deposit near Bathurst, New Brunswick, was detected. A variety of AEM systems was developed in Canada in the two decades that followed, and by 1970, 18 systems were used in exploration for massive sulphides. An overview of hardware development was given in Collett (1986). Most of the AEM systems were designed and operated by Canadian companies who at that time carried out about 80 percent of AEM surveys in the Western world. Annual production reached a stable level between 500 000 and 600 000 line km from 1967 until 1973. A similar level of activity was reached again during a three-year period 1979-1981, but since then the annual kilometrage has been declining (Palacky 1986). The latest figures indicate a production of 251 194 km for 1986 (Montgomery 1987), which is actually a significant improvement over 158 478 km flown in 1985 (Montgomery 1986). Perhaps the main reason for the decline has been the narrow scope of AEM applications — until recently most surveys have been carried out to aid prospecting for massive sulphide orebodies. Because of overproduction, the demand for base metals has sharply declined in the 1980s.

A broader concept of AEM usage was pursued in Finland, where the government (Geological Survey of Finland) started a systematic airborne EM/magnetic coverage in 1954. The program was completed in 1972, but in the same year a more detailed coverage using a tighter line spacing (200 m) and lower terrain clearance (30 m) was initiated. Until 1985, 1 476 000 line km were flown (Peltoniemi 1986). A similar program, though on a more limited scale, was started in 1969 by the Government of Québec, and until 1985, 111 720 km² were covered using a line spacing of 200 m (Lefebvre *et al.* 1986).

At present, only two types of AEM instruments are being operated in Canada, multifrequency, multi-coil helicopter systems and towed-bird, time-domain systems. Such systems were already in operation during the Exploration '77 meeting. At that time, the time-domain systems accounted for about 70 percent of all AEM surveys flown in Canada; today they represent less than 40 percent (Montgomery 1987). The presently used helicopter systems have been designed by two companies, Digheem Surveys and Data Processing Incorporated

of Mississauga and Geotech Limited of Markham. The time-domain systems include the INPUT[®] Mk VI operated by Questor Surveys Limited of Mississauga and the GEOTEM[®] system designed and operated by Geotrex Limited of Ottawa (all Canadian-based companies).

Despite efforts by several organizations, no significant breakthroughs in AEM concept or hardware have been achieved during the last 10 years (not considering the transition to digital receivers). None of the new-generation systems considered promising at the time of the Exploration '77 meeting (Becker 1979) became operational. On the other hand, the developments in computer technology have profoundly changed the data handling procedures which today at the time of writing are fully automated. The concepts of computer data processing of AEM data first outlined in Palacky and West (1974) still remain valid. Stacked profiles of INPUT[®] channels and conductivity (or resistivity) maps have become routine. The speed of the transformation has caught some geophysicists by surprise and many interpreters have not been able to digest the variety of new products and satisfactorily explain the vastly increased number of anomalies. While advances have been achieved in computer modelling of complex geometric situations (West 1986), less attention has been paid to correlation between geology and results of AEM surveys. An increased effort in this direction is necessary in order to broaden the appeal of the technique to exploration geologists, hydrologists, and other geoscientists, and thus reverse the downward trend in AEM usage. Several studies describing new applications have recently been published: geological mapping (Palacky 1981, 1987), kimberlite detection (Macnae 1979), uranium exploration (Fouques et al. 1986; Jagodits et al. 1986), groundwater prospecting (Paterson and Reford 1986), saline-intrusion mapping (Sengpiel 1986), geothermal exploration (Hoover and Pierce 1986), Quaternary mapping (Deletie and Lakshmanan 1986), detection of paleochannels and soil-salinity mapping (O'Connell and Nader 1986), and shallow-ocean bathymetry (Holladay et al. 1986; Won and Smits 1986; Zollinger et al. 1987).

CONDUCTIVITY CHARACTERISTICS OF GEOLOGICAL BODIES

Before the advent of multifrequency and broadband AEM systems, the most realistic survey targets were geological bodies having an *in situ* conductivity in excess of 100 mS/m. The technique could then be used to map massive sulphide bodies, graphitic bands, shales, Quaternary clays, and some more conductive weathered layers. The tendency was to consider only hard-rock conductors and disregard

"overburden" anomalies. Experience in tropical countries has proven that a unique identification of hard-rock conductors is extremely difficult without a comprehensive conductivity determination for all anomalies. Careful interpretation of AEM data has shown that consistent anomaly patterns are associated with certain geological formations (for example mafic volcanic rocks). Thus, it became possible to produce pseudogeological maps from AEM data and to substantially upgrade geological maps after field checks (Palacky 1981).

Developments in instrumentation and data processing have significantly enhanced the detection capabilities of AEM systems which now cover a conductivity spectrum from 0.1 mS/m to 100 mS/m. Figure 15.1 depicts earth materials that can be detected by modern AEM systems. The most typical situation in shield areas comprises resistive igneous and metamorphic rocks occasionally containing conductive massive sulphide bodies and graphitic layers. Unless the area is subject to a rapid tectonic uplift, a multilayer weathered cover develops in the upper 10 to 100 m. Its development and composition are described in this paper. In formerly glaciated areas, the weathered layer was partly or completely eroded and Quaternary sediments (tills, gravel, sand, clay) were deposited either directly by glaciers or by lakes and rivers during interglacial periods. Therefore, the conductivity section may be quite complex in many parts of Canada, the USSR, and northern Europe. Conductivity of sedimentary rocks may range within wide limits and the bars in Figure 15.1 do not provide more than a crude, schematic representation. Shales are almost invariably more conductive than other sedimentary rocks in the lithological sequence, but their actual conductivity will vary widely depending on porosity, water saturation, water conductivity, and the type of clay minerals present. Only few AEM surveys have been carried out in sedimentary areas. The state, temperature, and chemical composition of contained water will affect the measured conductivity in many situations. Often, one can deduce from the AEM data ground salinity (for example, identification of aquifer types), or determine thickness of frozen ground (permafrost) or sea ice. Conductivity characteristics of geological targets were described in detail in Palacky (1988).

This paper focuses on developments in interpretation of AEM data achieved during the last decade. Apart from improvements in data processing and presentation, the most significant advance has been a better understanding of electrical properties of the weathered layer and Quaternary sediments.

ELECTRICAL PROPERTIES OF THE WEATHERED LAYER

Weathering is a complex chemical process which results in decomposition of some primary rock-forming minerals and their substitution by clay minerals. Water-saturated clay minerals make the alteration

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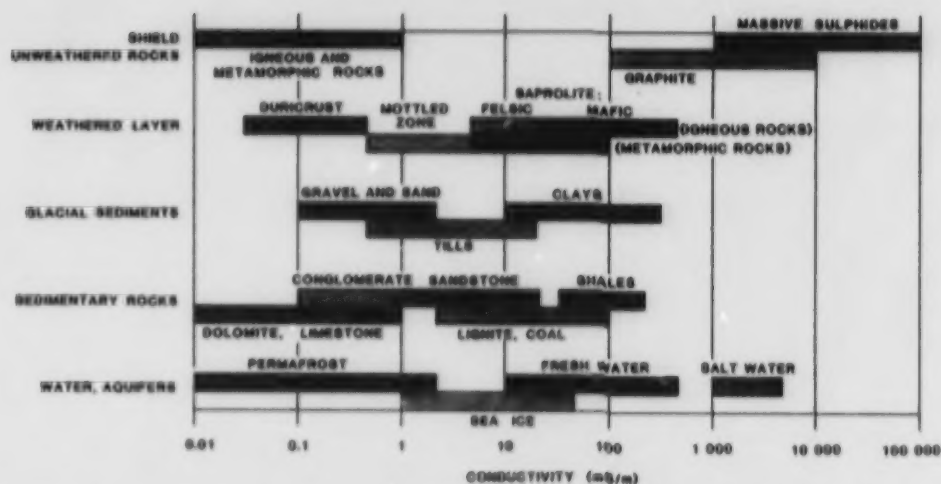


Figure 15.1. Conductivity ranges for commonly occurring earth materials (modified from Palacký 1987).

zone significantly more conductive than the parent rock. Most igneous rocks are resistive when fresh (Angeheister 1982). Their average conductivity values range from 0.15 mS/m for diorite and 0.2 mS/m for granite to 2 mS/m (diabase, gabbro). Conductivity is highly variable, but fresh igneous rocks with values over 5 mS/m are extremely rare. The values quoted were obtained by *in situ* measurements; laboratory determinations yield significantly lower values (between 0.01 and 0.5 mS/m). Figure 15.2 shows weathering profiles for felsic and mafic igneous rocks. A complete profile is composed of the following zones (Butt 1982):

1. Fresh rock, which has a conductivity generally less than 2 mS/m.
2. A zone of fractured rock whose mineral composition is identical to that of fresh rock. The

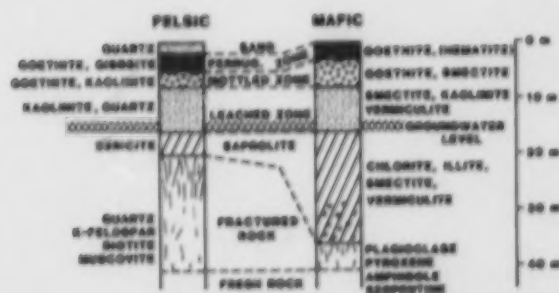


Figure 15.2. Schematic weathering profiles developed over felsic and mafic igneous rocks. The minerals most common to each horizon are written on the outside of the columns. Names of the components of the weathered profile are given in the middle column. The depth scale (in m) is schematic and significantly thinner or thicker sequences can be found throughout the world (after Palacký 1987).

names of the most common minerals are listed in the figure. Typically, this zone is thicker over felsic rocks.

3. Saprolite, the layer immediately below the water table, in which the original rock textures are still preserved by stable primary minerals and newly formed secondary clays. Saprolite is the most conductive component of the weathered layer.
4. A leached zone, which develops when the region becomes progressively arid, or when it is subjected to a gradual uplift. The resulting lowering of the water table causes leaching of the upper part of the saprolite layer. Depending on the local conditions, saprolite may be completely leached (with a resulting decrease in conductivity of the weathered layer), or the leached zone may be totally absent, or most commonly, one will observe an intermediate situation. Usually, saprolite remains thicker than the leached zone.
5. A mottled zone, which develops from saprolite before leaching, but the process may continue even in conditions described above. In the mottled zone, some of the clays formed during the saprolite-formation stage have been replaced by second-generation clay minerals. Mobile constituents are increasingly lost. This zone is only moderately conductive.
6. A ferruginous zone, which is enriched in iron oxides, particularly hematite. Pisolitic concretions form near the transition from the mottled zone. Dehydration of the uppermost ferruginous zone, which is common in regions with well-defined dry-wet seasons, leads to its hardening and to the formation of duricrust (called "canga" in Brazil, "cuirasse" in West Africa). This zone is highly resistive (conductivity less than 0.5 mS/m).

7. A sand layer, which is formed when leaching progresses under acid and oxidizing conditions. It is more common in areas underlain by felsic igneous rocks.

The thickness of the weathered layer depends on many factors, including lithology, topography, climate, and tectonic movement. In many regions of Australia, it exceeds 100 m but elsewhere 20 to 50 m would be normal. Many investigations concerning the development and properties of the weathered layer originated in Australia (for example, Butt 1982). Significant geophysical research concerning application of EM techniques in areas of intense weathering was also carried out in that country (for example, McCracken *et al.* 1986a, 1986 b). In this paper, I have followed the Australian convention of describing the weathered layer components. This convention has also been adopted by the Geological Survey of Canada. However, many European geologists use the term "chloritization zone" rather than saprolite. The term "regolith" for the whole weathering sequence, commonly used in Africa and North America, has been avoided here. Occasionally, the term saprolite is used to designate the leached and mottled zone, or is even used as a synonym of the weathered layer.

It would be wrong to assume that weathered layers are well developed only in tropical regions. Unless removed by erosion, such layers have remained preserved from past geological times when the climate was more conducive to chemical weathering (for example, Tertiary in Europe and Australia). Saprolite is present in many parts of Canada which now have a very cold climate (for example, Labrador Trough, Arctic Islands), and in many deserts of Australia and Africa where the present climatic conditions would favour mechanical rather than chemical weathering. Saprolite is also common in many parts of Europe. On the other hand, the weathered layer can be thin or even absent in hilly areas in tropical regions which are undergoing a rapid tectonic uplift (for example, Jamaica, parts of Thailand). Saprolite is also poorly developed in areas which had a consistently arid climate since the last tectonic uplift (for example, parts of the Arabian Peninsula, Namibia). Intense leaching common in superhumid climates (for example, coastal West Africa, the Amazon Basin) results in the removal of saprolite and its replacement by the leached zone.

Electrical properties of the weathered layer depend on the relative importance of saprolite, leached and mottled zones, and their mineralogical composition. Figure 15.3. shows the results of well-logging of two holes drilled in the Musongati peridotite massif in Burundi. The measured resistivity values were converted to conductivity to highlight the conductive saprolite layer. Maximum values of 160 mS/m were obtained in both holes. Both the underlying fresh rock (peridotite) and the overlying mottled zone and duricrust are significantly less con-

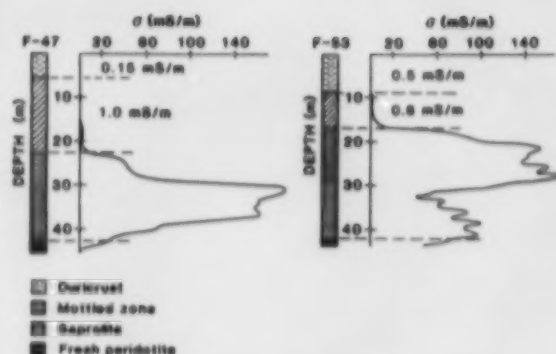


Figure 15.3. Geological and conductivity logs of the weathered layer developed at the Musongati peridotite massif in Burundi. Conductivity logs were obtained by processing the results of three-electrode resistivity measurements in boreholes (modified from Peric 1981).

ductive (less than 1 mS/m). Electrical properties of the Musongati Massif, where saprolite hosts economic accumulations of nickel, have been described in Peric (1981). Numerous vertical electrical soundings carried out in the area yielded similar resistivity values for saprolite — between 5 and 25 Ω -m, which correspond to a conductivity range of 40 to 200 mS/m. The average saprolite thickness was 18 m.

A comparison with results obtained elsewhere indicates that these values are fairly typical of weathered layers developed over peridotite. Analyzing results of vertical electrical soundings carried out over a peridotite massif near Canabrava, Goiás, Brazil, Palacky and Kadekaru (1979) came up with a mean value of 125 mS/m and a standard deviation of 40 mS/m (based on 13 soundings). The average thickness of saprolite was 21 m. Saprolite developed over neighbouring basalts was generally less conductive (mean 51 mS/m) and thinner (mean 11 m).

Vertical electrical soundings were used by the same group (Palacky and Kadekaru 1979) to determine weathering patterns in other regions of Brazil. The most complete weathering profiles were obtained in the Central Planalto (State of Goiás) which has a well-defined bi-seasonal climate (wet and dry). Figure 15.4 shows a weathering profile over a dunite massif near Santa Fé, Goiás (250 km west of Brasília). The saprolite layer in this section is between 22 and 30 m thick and has a fairly constant conductivity (20 mS/m). One pit reached the top of this layer. The thinner mottled zone has a much lower conductivity (average 1.2 mS/m) and would be undetectable using most EM systems. Because of the type of electrical layering (resistivity decreasing with depth), it is often difficult to accurately establish the transition from the mottled zone to saprolite from vertical electrical sounding data. Near surface,

the fairly thin ferruginous zone (about 5 m) is hardened to "canga" (duricrust). Electrical soundings identify it as a highly resistive layer with conductivity generally less than 0.1 mS/m.

As Figure 15.2 illustrates, the mineral composition of saprolite varies according to the lithology of the parent rock. Conductive clay minerals are more abundant in mafic and ultramafic rocks than in felsic igneous rocks and *in situ* conductivity measurements can be used to distinguish rock types of different mineral composition. Determinations of saprolite conductivity derived from ground and airborne EM measurements and vertical electrical soundings appear to be reasonably accurate, and the results can be used to compile pseudogeological maps. I have been involved in the interpretation of EM surveys in volcano-sedimentary areas in France, Spain, Portugal, Burkina Faso, Ivory Coast, Kenya, South Af-

rica, Australia, India, Thailand, The Philippines, Saudi Arabia, Brazil, Canada, and USA, and everywhere, the conductivity of saprolite developed over mafic rocks was locally higher than that over felsic rocks. Conductivities of saprolite formed from granite, andesite, basalt, and peridotite at several locations around the globe are given in Figure 15.5 which is based on published data compiled by Palacký (1987). The conductivity of granitic saprolite is consistently low (10 to 25 mS/m) despite the fact that the data were obtained in four continents. The value listed for Ottawa was determined by well-logging of paleosaprolite covered by 60 m of Paleozoic sediments. It is significant that saprolite did not lose its distinct electrical properties after a marine transgression, sedimentation, and tectonic uplift. Also, andesitic saprolite was found to have a rather low conductivity, with similar values being obtained in Australia and Brazil. A larger variation has been observed in conductivity of basaltic saprolite, ranging from less than 30 mS/m to 200 mS/m, but one should keep in mind that conductivity behaves essentially in a logarithmic fashion (e.g. a change of few units is more significant for discrimination of poorly conductive rocks than a change of hundreds of mS/m for highly conductive materials). Saprolite over peridotite has been found consistently conductive, with average values in excess of 100 mS/m.

In metamorphic areas, saprolite developed over some lithologies, notably amphibolite, can be highly conductive. Values of 100 mS/m appear to be typical in West Africa (determinations in Mali and Burkina Faso (see Palacký 1987). Gneissic saprolite, on the other hand, is fairly resistive (10 mS/m). A significant variation in conductivity has been observed over schistic saprolite in different parts of the world (between 8 and 50 mS/m). In common usage, the term schist may be applied to rocks whose tex-

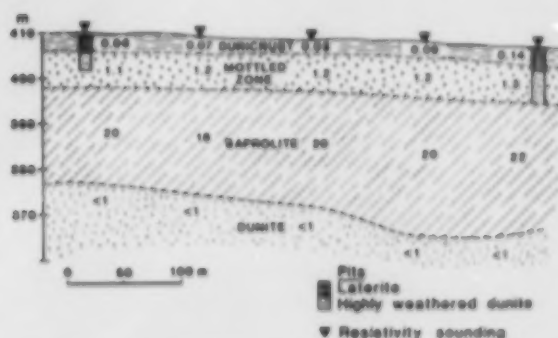


Figure 15.4. Geological section of the weathered layer at Santa Fé, Goiás, Brazil. Layer thickness and conductivity values (in mS/m) were interpreted from the results of vertical resistivity soundings (modified from Palacký and Kadekaru 1979).

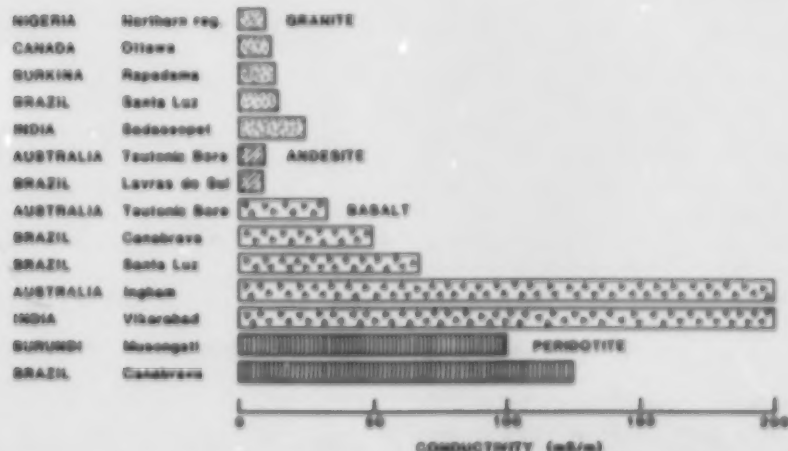


Figure 15.5. Conductivities of saprolite layers developed over igneous rocks. The values are based on resistivity soundings, borehole logging, or EM surveys. The graphs are based on tables in Palacký (1987).

ture and chemical composition significantly differ. What is important is that in any given area, conductivity determinations for many rock types were within a rather limited band, thus allowing lithological identification from results of EM or resistivity surveys.

GEOLOGICAL MAPPING IN SHIELD AREAS

As mentioned in the Introduction, the AEM technique was developed as a tool of prospecting for volcanogenic massive sulphide orebodies. The exploration sequence, consisting of airborne geophysical surveying, anomaly selection, ground follow-up and drilling, has been highly successful in the Canadian Precambrian Shield (Paterson 1970). However, when attempts were made to apply it elsewhere (Australia, Brazil, India, various African countries) the approach usually failed and no orebodies were discovered as a direct result of geophysical surveying. The critical link in the sequence is anomaly selection, and empirical criteria established in Canada were not applicable because of a larger variety of detected conductors. In northern countries that underwent glacial erosion, conductors could be separated into two categories: a) "bedrock" (massive sulphides, graphite), and b) "overburden" (glacial and glaciolacustrine sediments). The two anomaly types could be easily identified by their shape on AEM records and from estimated conductivity values.

When conductive overburden was encountered in tropical countries, the recommended course of action was to modify the instrumentation to eliminate "overburden" anomalies, either by significantly lowering the instrument frequency — Unicoll (Morrison *et al.* 1976), or by establishing characteristics of sulphide conductors and recognize them by in-flight computer processing — COTRAN* (Collett *et al.* 1983). Had the projects been successful, one would have reverted to the "Canadian" exploration scheme. Despite millions of dollars spent on their development in the 1970s, both developments failed because the new used technology was too difficult to master, or was too expensive to put to practical use. At the same time, many explorationists started questioning the validity of the described exploration sequence. By 1980, it was widely realized that mineral exploration based on blanket coverage by AEM methods cannot be conducted without a significant geological input, and attention turned to systems that could provide comprehensive and unbiased information — conductivity maps rather than bull's eyes with recommendations for follow-up and drilling.

Though the acceptance of AEM techniques for geological mapping is new (certainly since the last Exploration '77 meeting), the concepts have been known for a long time. Such usage of AEM surveys has been practiced in Finland and the USSR since

the 1950s, but surprisingly, it had little impact on thinking in North America. Algorithms to generate conductivity maps from AEM data were described already during the last decade (Fraser 1978; Palacky 1972) but this approach aroused only a limited interest in the exploration community despite a clear correlation between EM responses and lithology. When interpreting INFUT results from the Project Pioneer in Manitoba, Dyck *et al.* (1975) pointed out a striking correlation between AEM anomalies and certain lithological units but instead of generalizing their findings, the authors explained the anomalies by assuming an unusually conductive peridotite. They did not identify uneroded saprolite layers as the source of the AEM anomalies.

ITAPICURÚ GREENSTONE BELT, BAHIA, BRAZIL

Most of the pioneering studies relating AEM anomalies to lithology were done in Brazil in the late 1970s. Data from INPUT and helicopter AEM surveys flown in 1976 to 1977 were reprocessed and conductivity maps compiled. Because of the limitations of analogue data sets and the state of geophysical technology, not all data points were used in the compilation and maps consisted of discrete conductivity bands rather than contours. Generally, the homogeneous half-space model was used in the compilation. While this model may not be the most suitable for all situations, its simplicity is appealing. A vertical half-plane nomogram (Palacky and West 1973) was used to estimate conductivity of bedrock conductors which were considered for ground follow-up. Conductivity maps proved extremely useful and were used by geologists to update geological maps.

Figures 15.6 to 15.8 illustrate such a process for one segment of the Itapicuru survey in the State of Bahia. The Itapicuru Greenstone Belt, which ex-

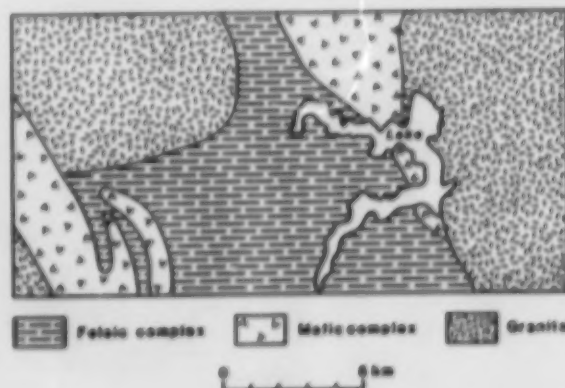


Figure 15.6. Original geological map of an area in the Itapicuru Greenstone Belt, Bahia, Brazil, based on aerial photography and ground reconnaissance (after Palacky 1981).

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Figure 15.7. Improved geological map of the area in Figure 15.6 based on interpreted AEM maps and ground checks (modified from Palacký 1981).

tends north-south for a distance of 90 km, lies 180 km north-northwest of Salvador, the state capital (Latitude 11°S). Kishida and Riccio (1980) defined three lithological units in the belt:

1. metavolcanic mafic unit with metabasalts, graphitic schists, iron formations, and intrusive gabbro dikes and sills
2. metavolcanic felsic unit composed of felsic and intermediate metavolcanic rocks, felsic lavas, volcanic breccias and tuffs
3. metasedimentary unit consisting of conglomerates, arkoses, pelites, and graywackes with frequent graphitic layers

The greenstone belt is almost entirely surrounded by Archean granite-gneiss massifs which are thought to be contemporaneous with the greenstone belt.

Original geological mapping, which was carried out during the initial phases of the mineral exploration project by Rio Doce Geologia e Mineração, was based on aerial photography and ground reconnaissance (mostly recording soil colour changes). The almost total absence of outcrops outside the granite-gneiss massifs made such an approach difficult and time-consuming as access is limited in roadless areas covered by dense thorny vegetation (catinga). In the original mapping, only three units were recognized: 1) granite, 2) felsic unit, and 3) mafic unit (see Figure 15.6).

Conductivity anomaly patterns are more complex than the original geological map. For instance, EM data indicate that granite, which coincides with resistive areas, has a much smaller extent than previously thought (northwestern corner and eastern quarter in Figure 15.7). Fragments of granite, which do not decompose easily, are found scattered over a distance of more than 1 km from its source. Neither aerial photography nor magnetic maps (Figure 15.8) indicate extensive amphibolite lenses whose existence was verified in the field after their identification on conductivity maps. Saprolite formed over amphibolite causes INPUT anomalies of medium to small amplitude, indicating an average conductivity of 60 mS/m. Mafic volcanic rocks (basalt) were recognized by large-amplitude, wide anomalies which were detected over conductive saprolite (average conductivity 80 mS/m). While the standard deviation of conductivities determined over mafic volcanic rocks was rather low (about 20 mS/m), it was higher (up to 35 mS/m) over amphibolite. Geologi-

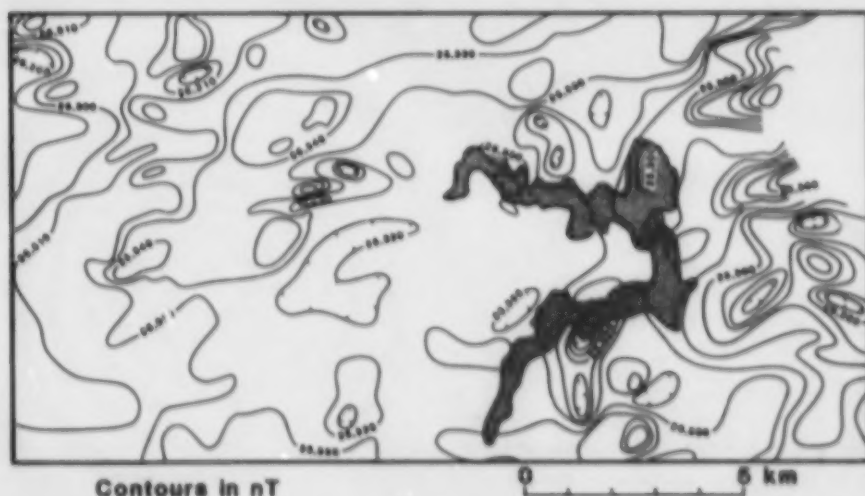


Figure 15.8. Magnetic map (total field) of the area depicted in Figures 15.6 and 15.7. The line spacing was 300 m, the mean sensor height 100 m. Magnetic patterns do not reflect lithological changes (modified from Palacký 1981).

cal interpretation and field checks were important in drawing the formation boundaries. The confirmed extent of volcanic rocks is much smaller than thought previously (see the southwestern corner). According to their conductivity characteristics, three sedimentary rock types could be identified: a) resistive clastic sediments (conglomerate), b) chemical and pelitic sediments (medium to small INPUT amplitudes), c) graywackes with graphitic layers (large to medium amplitude, sharp peaks, average conductivity 120 mS/m with standard deviation of 40 mS/m). Unlike basalt and amphibolite areas, where the conductor (saprolite) is a product of weathering, sedimentary areas have sequences of bedrock conductors (graphite, shale). Applying a uniform interpretation model to the data, the effect of saprolite and sediment thickness has largely been neglected. This simplification has caused high standard deviations over formations whose thickness is variable. If the area were more rugged with highly variable saprolite thickness, the approach would result even in higher standard deviation in apparent conductivity determinations.

Magnetic data are considered useful in geological mapping, but in this area the magnetic map (Figure 15.8) showed hardly any correlation with the geological map. The patterns indicate only a less magnetic granite in the eastern part of the area. Total magnetic field is very low, slightly over 25 000 nT, in the area. The limited usefulness of magnetic data for geological mapping is typical not only of the Itapicuru Greenstone Belt but of many other Precambrian areas in Brazil as well. This fact was the major driving force in the development of more sophisticated ways of interpreting AEM data. Geophysical staff of Rio Doce Geologia e Mineração reinterpreted AEM data and presented them in the form of pseudo-geological maps in other exploration areas (for example, Andorinhas in Pará, Vale do Curuçá in Bahia, Caçapava do Sul in Rio Grande do Sul). Since the late 1970s, airborne geophysics has contributed to several mineral discoveries in Brazil (gold in Bahia and Mato Grosso do Sul), but almost invariably in an indirect way by improving geological knowledge of the explored area rather than by pinpointing the orebody.

LABRADOR TROUGH, QUÉBEC, CANADA

The Labrador Trough is a major geological structure in northern Québec, extending for over 1200 km from the border with the Grenville Province (Latitude 53°30'N) to the Ungava Peninsula (Latitude 62°N). The Trough borders the Superior Province in the west, and Churchill and Nair Provinces in the east. Early Proterozoic igneous and sedimentary rocks of the Trough overlie an Archean basement.

The southern part of the trough was of economic importance — iron ore was mined near Schefferville from the 1940s until 1983. Since the 1930s, detailed geological studies have been carried out in the area

by the Geological Survey of Canada, Québec Ministry of Energy and Resources, and several mining companies, particularly Iron Ore Company of Canada. In 1983, the Québec Ministry of Energy and Resources commissioned extensive airborne geophysical surveys. A total of 14 836 line km was flown with the time-domain INPUT system and 36 075 line km with a multifrequency, multicoil helicopter AEM system (Lefebvre *et al.* 1986). Some of the INPUT data were reprocessed by A-Cubed Incorporated in the form of stacked magnetic and EM profiles (OUTPUT). This data presentation, which preserves the shape of the measured anomalies permits easier identification of conductor types (bedrock, saprolite).

As example of AEM interpretation, data from the Thompson Lake area will be described. Figures 15.9, 15.10, and 15.11 show respectively geology, total magnetic field, and OUTPUT pseudo-channel 6 derived from INPUT data. AEM response at the delay time of 2.28 msec (channel 6) is free of any effect poor conductors (glacial sediments) may have on INPUT measurements.

Rocks belonging to three groups of Proterozoic age were identified in the depicted area. The oldest is the Doublet Group represented here by three formations (Murdock, Thompson, and Willbob). The geological descriptions given below are based on Dimroth (1978). The Murdock Formation, which crops out in the southwestern corner, coincides with an area of strong magnetic activity. The formation is made of predominantly pyroclastic rocks with subordinate basalt flows and sedimentary rocks. A strong AEM trend consisting of five anomalies indicates the true extent of the mapped gabbro (Montagnais Group). Most likely, the anomalies are due to saprolite developed over this rock type.

Numerous AEM anomalies are associated with pelitic schists of the Thompson Lake Formation. The schist sequence consists of graphitic or pyritic shales, and locally, massive pyrite beds were observed. All mentioned rock types may be highly conductive. As they are poorly exposed and sometimes weathered (particularly graphitic shales), AEM results can be used to improve the accuracy of geological maps. Volcanic and intrusive rocks also belong to the Thompson Lake Formation, but often they have been mapped as Montagnais Group (a convenient catch-all for gabbroic and ultramafic rocks which are usually difficult to identify). No significant magnetic anomalies are associated with the Thompson Lake Formation.

The Willbob Formation, which covers almost half of the illustrated area, consists of pillowed and massive basalt flows with interbedded thin layers of graphitic or pyritic shales. Geological reports mention that basalt is frequently weathered (light grey-green colour), suggesting saprolite presence. Both shales and saprolite are usually conductive. No magnetic anomalies, but numerous strong AEM trends

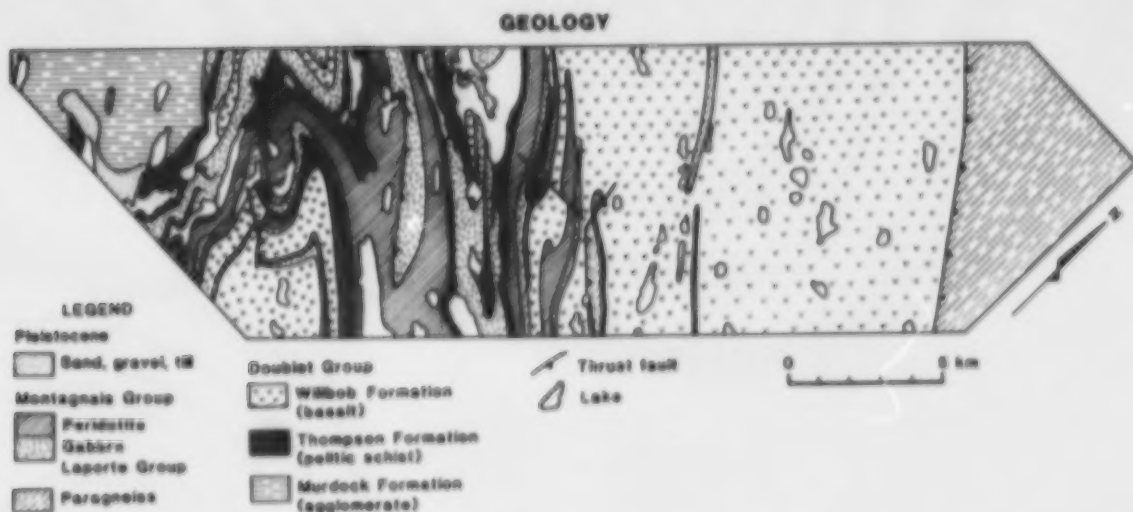


Figure 15.9. Geological map of the Thompson Lake area, Labrador Trough, Québec, Canada (excerpted from Dimroth 1978, sheet Lac Bacchus 1862, scale 1:50 000).

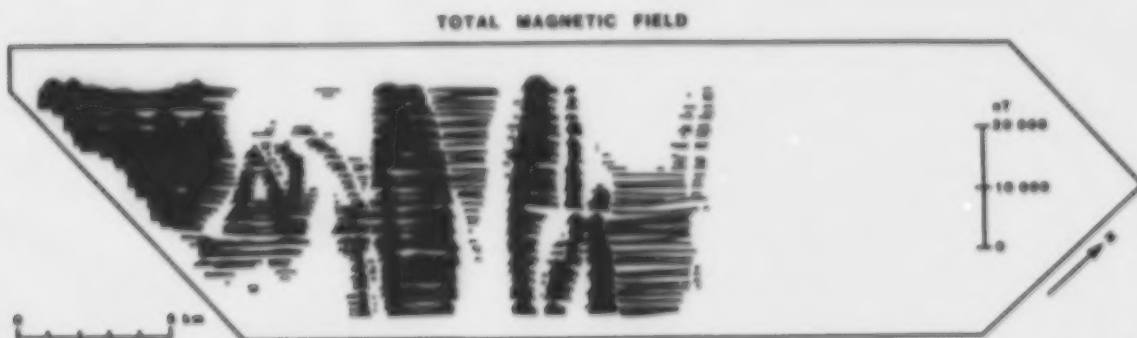


Figure 15.10. Stacked magnetic profiles (total field) of the area of Figure 15.9. The survey line spacing was 200 m, the mean sensor height 100 m (courtesy of A-Cubed Incorporated).

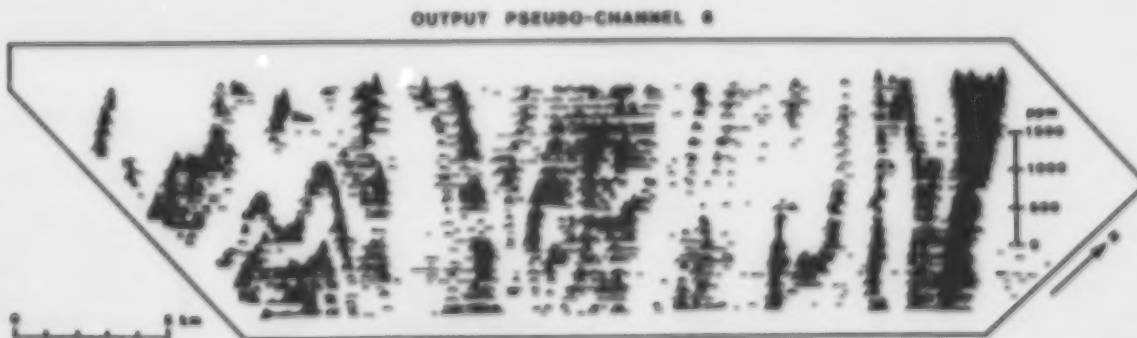


Figure 15.11. Stacked channel 6 OUTPUT profiles indicate conductive formations (area of Figure 15.9). The profiles were obtained by processing of INPUT data (courtesy of A-Cubed Incorporated).

can be observed in areas underlain by this formation.

The Doublet Group is separated by a thrust fault from the Laport Group which crops out in the north-eastern corner of the described area. Strong AEM anomalies were detected just northeast of the fault, but the present geological map does not offer any explanation for their existence. The lithology has been described locally as a sequence of meta-quartzite, metamorphosed dolomitic sandstone, aluminous pelite, amphibolite, and ultramafic rocks. As neither pyritic nor graphitic schists are known to occur in this formation, it can be assumed that the detected anomalies are due to saprolite developed over amphibolite or ultramafic igneous rocks.

The already mentioned Montagnais Group includes all poorly defined gabbroic and ultramafic igneous rocks in the Labrador Trough. Originally, the rocks were thought to be intrusive, but recent studies have shown that many are of extrusive origin and thus can be included with their host formations. As strong magnetic anomalies are associated with peridotite, magnetic surveying has been extensively used to map their extent. Gabbro does not appear to cause magnetic anomalies but AEM response has been recorded. Chloritization has been described in the area and chlorite-rich layers can be conductive. A careful analysis of AEM data can contribute to a better discrimination of units in this poorly understood group.

A brief analysis of AEM anomalies in this small part of the Labrador Trough (35 by 9.5 km) has not (and without extensive field work could not have) provided any definite answers. However, it certainly raised attention to the fact that AEM patterns can be complex (even more than magnetics) and that many AEM anomalies associated with "overburden" provide information on bedrock rather than Quaternary geology. Interpretation techniques established in non-glaciated regions, where the effect of weathering on EM response is better understood, can be put to test in this part of Canada.

MAPPING OF QUATERNARY GEOLOGY

Since the early 1980s, attempts have been made in Canada to use AEM techniques for mapping the lithology and thickness of glacial and glaciolacustrine sediments (Picher *et al.* 1984). In France, helicopter EM surveys have been applied to mapping of Quaternary alluvia and underlying Tertiary strata (Deletie and Lakshmanan 1986). The Geological Survey of Canada has been involved in airborne and ground EM surveys designed to map Quaternary sediments since 1985. The project is financed under the Mineral Development Agreement with the Province of Ontario.

In the first phase of the program, airborne and ground surveys were carried out at the Val Gagné



Figure 15.12. Conductivity map (contours in mS/m) of the Val Gagné test site, Ontario, Canada. The map was compiled using horizontal coplanar Helicopter EM data at the frequency of 4175 Hz. The line spacing was 100 m, the sensor height 30 m.

test site, 60 km east of Timmins. The test site (6.4 by 2.6 km) is located in the clay belt. Locally, the thickness of clayey glaciolacustrine sediments varies between 10 and 50 m. So far, the most accurate information on composition and thickness of Quaternary sediments has been obtained from shallow reflection seismic surveys (Pullan *et al.* 1987). Results

of helicopter EM surveys were compiled as conductivity and depth-to-bedrock maps derived from various coil configurations and frequencies. A 4-frequency system was used in the survey (vertical coaxial coil pairs at 935 and 4600 Hz, horizontal coplanar coil pairs at 4175 and 32 000 Hz). A conductivity map obtained with a horizontal coplanar coil pair operating at 4175 Hz is shown in Figure 15.12. A thick horizontal-layer model was used in conductivity calculations. The average conductivity (25 mS/m) is somewhat lower than values derived from ground EM and resistivity measurements (30 mS/m). A pronounced resistivity low running almost diagonally across the northern half of the test site corresponds to the Black River. Presumably, the thickness of clays is reduced underneath the river bed as more clastic sediments are transported by the river. Generally, the cover of clayey glaciolacustrine sediments is thinner north of the Pipestone Fault which runs east-west, 2 km south of the northern border of the area. After assessment of the results at the Val Gagné test site, a recommendation was made to use helicopter EM measurements in Quaternary mapping programs in northern Ontario.

In early 1987, transect helicopter EM surveys were flown north and south of Kapuskasing and from Smoky Falls to Timmins (via Fraserdale and Smooth Rock Falls). Transect surveys consist of two lines flown along selected roads. The data were processed in the form of composite profiles and colour bar maps. Follow-up using ground EM equipment was carried out in the summer of 1987 and drilling immediately followed.

Plate 15.1 (see Colour Folio near end of volume) shows a colour-bar profile of apparent conductivity derived from the helicopter EM survey

data. The profile is 8 km long and it is located 35 km south of Kapuskasing. The colour coding ranges from purple and blue for resistive material (less than 0.2 mS/m) to green, orange, and red for conductors. Data obtained with two horizontal coplanar coils (frequency 4175 and 32 000 Hz) were used in conductivity calculations. Using the same colour bar presentation, Plate 15.2 (see Colour Folio) displays depth to bedrock calculated from the two coplanar data sets. Colour coding uses cold colours (purple and blue) for shallow bedrock (less than 30 m), various shades of green for intermediate depth (30 to 90 m), and yellow and red for deep valleys. A conductivity value of 30 mS/m which is typical of glacial clays was assumed throughout. As this conductivity is too high for other Quaternary sediments, depth estimates become unreliable (too shallow) in segments where gravel, sand, or till predominate. The third data set illustrated (Plate 15.3, see Colour Folio) are total-field VLF responses which were measured using a two-frequency Herz Totem 2A receiver. Conductors have a positive response (warm colours). AEM data can be better scrutinized in the form of composite profiles (Plate 15.3). From the top, the following parameters are displayed: inphase and quadrature components for vertical-coaxial-coil data (low and high frequency), inphase and quadrature components for horizontal coplanar coil configuration (low and high frequency), and two apparent conductivity traces calculated from the coplanar data using a thick horizontal-layer model.

Three areas depicted in Plates 15.1 to 15.3 were investigated by ground geophysical surveys and drilling. The used equipment was a multifrequency horizontal-loop EM (HLEM) system (APEX Max Min I). Inphase and quadrature responses at 110, 220,

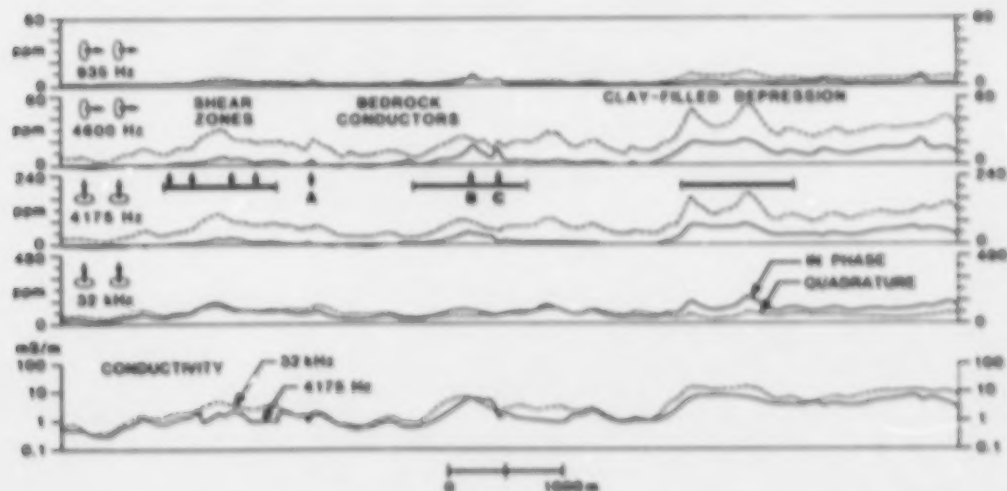


Figure 15.13. Composite profile of measured helicopter AEM data (inphase and quadrature components at 4 frequencies, 2 coil configurations) and calculated conductivity based on horizontal coplanar data. Segment 4, Kapuskasing Transect.

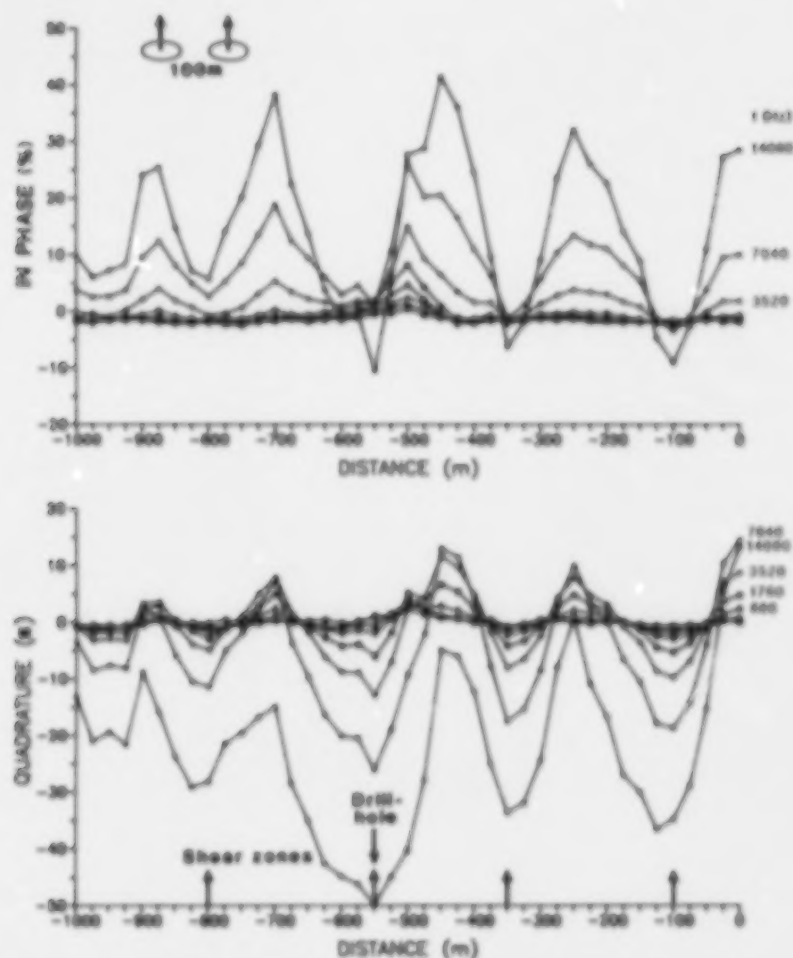


Figure 15.14. Horizontal-loop EM data (inphase and quadrature) for 8 frequencies. The location of this follow-up survey is indicated in Plates 15.1, 15.2, 15.3 and Figure 15.13 by bars and annotation shear zones. Description of drilling at -550 in the text.

440, 880, 1760, 3520, 7040 and 14080 Hz are presented in Figures 15.14 to 15.16 and Figure 15.13. In the most southerly area, four shear zones were detected. While their response is characteristic on the HLEM data, trough-like anomalies which are wider on quadrature than on inphase data, the AEM results indicates only a small increase in the quadrature response. A depth-to-bedrock estimate based on low-frequency AEM data (4175 Hz) is quite accurate (9 m) when compared with the results of drilling. A vertical reverse-circulation hole at -550 reached bedrock at 8.5 m after intersecting Quaternary sand and clay. In the second area, both AEM and HLEM surveys clearly identified two bedrock conductors at -515 and -275 m on the ground follow-up profile. A vertical drillhole at -500 intersected 6 m of poorly sorted sediments, 14 m of sand, and 15 m of till and silt. Because of a disloca-

tion from the centre of the HLEM anomaly (about 15 m), the vertical drillhole could not intersect the narrow bedrock conductor (less than 5 m wide). The depth-to-bedrock determination based on low-frequency coplanar data (range 24 to 27 m) resulted in an underestimate because of the conductivity assumption which was too high for the encountered sediments. Using the same conductivity, interpretation of high-frequency data (32 kHz) resulted in a better depth estimate (36 to 39 m). The third follow-up area was selected to investigate a local increase in conductivity, presumably caused by clay accumulation. The interpretation proved correct, and a drillhole at -650 intersected 12 m of massive clays, 6 m of varved clays, and 17 m of sand. The low-frequency coplanar AEM data indicated a depth to bedrock of 30 m, somewhat underestimating the true depth of 35 m. The discrepancy is due

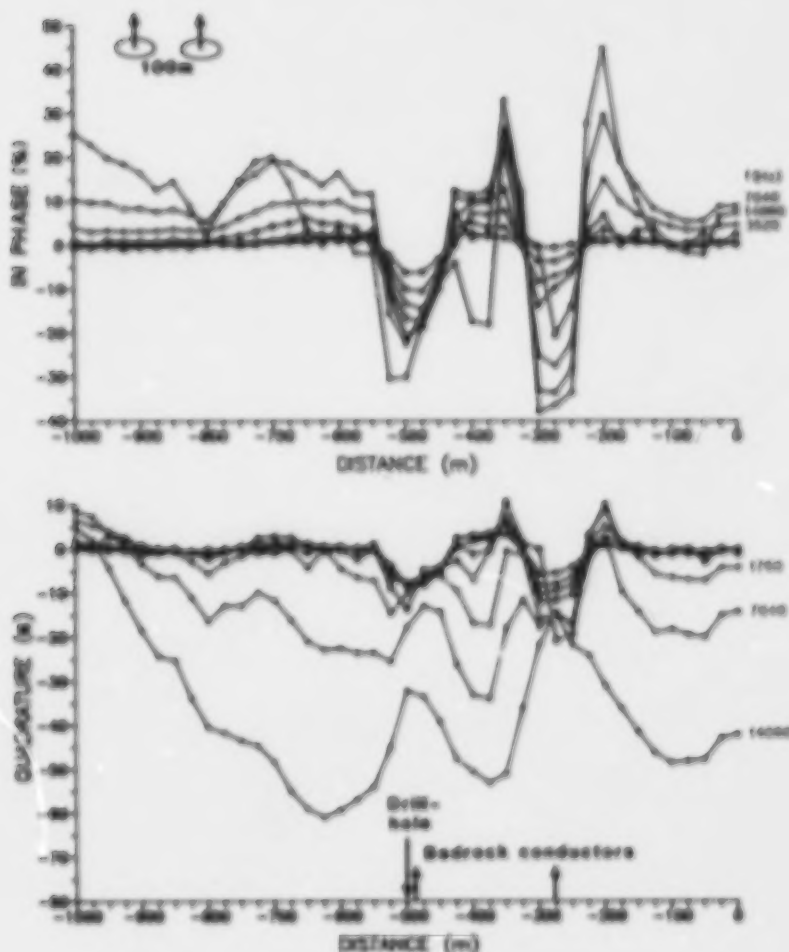


Figure 15.15. Horizontal-loop EM data — follow-up of bedrock conductors. Description of drilling at -500 in the text. The survey location is indicated in Plates 15.1, 15.2, 15.3 and Figure 15.15.

to a simplified assumption of one conductive layer overlying bedrock.

The concept of using AEM surveys for mapping of Quaternary sediments has been proven viable. Other transects have been checked by ground EM surveys and drilling, and discrepancy between reality and interpretation did not exceed 20 percent. There is a considerable scope to improve the interpretation of AEM data by using more complex models (3 or more layers), which are already available. The results of AEM surveys can be used to identify Quaternary lithology: conductive clay, resistive sand and gravel, and tills which usually have intermediate, but highly variable conductivity. When the conductivity of the Quaternary cover is realistically estimated, depth to bedrock can be reliably determined from AEM data. Helicopter EM surveys are very cost-effective, a line km of surveys costs about C\$50 to

60, compared with C\$500 for ground HLEM surveys, and C\$6000 for shallow-reflection seismics. VLF results have not been considered useful in this survey. A quick glance at the VLF map (Figure 15.16) suffices to see the lack of correlation between VLF and other data sets. Contrary to popular belief, VLF is not effective in mapping shear zones in areas covered by Quaternary sediments. The method can neither detect bedrock conductors under moderately thick (35 m) overburden cover, nor map conductivity changes caused by accumulation of clays.

CONCLUSIONS

Present-day AEM systems are capable of more than a simple detection of massive sulphide bodies in resistive areas. The most important new application is geological mapping. Multiparameter AEM data can

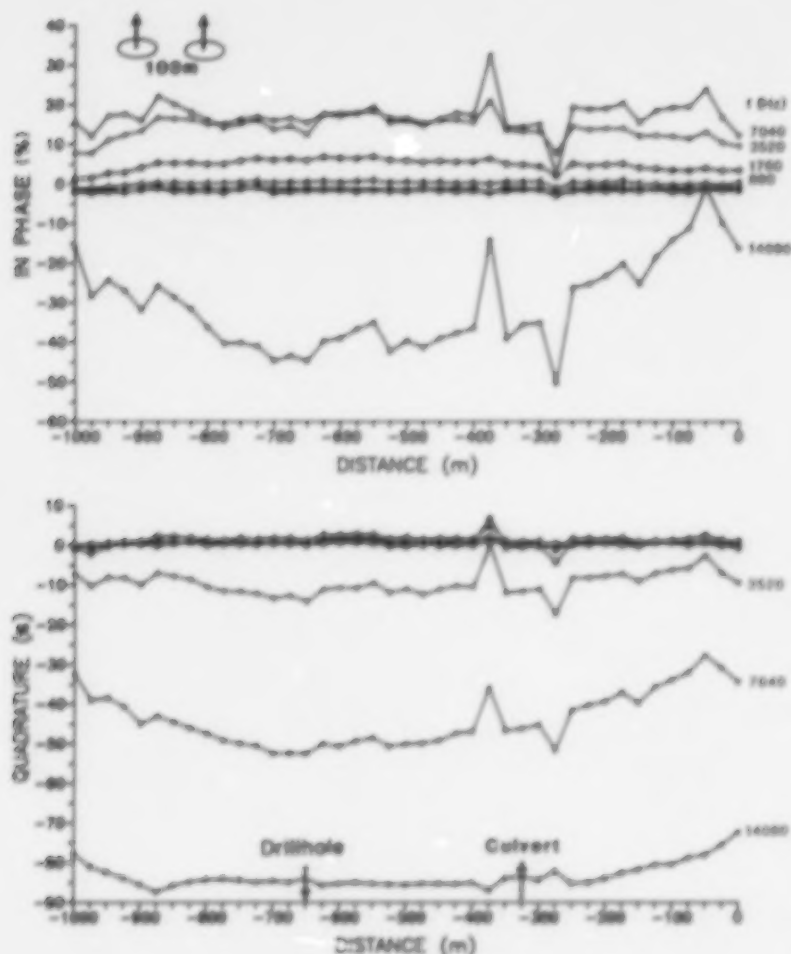


Figure 15.16. Horizontal-loop EM data — follow-up of a clay-filled depression. Drillhole at -650 is described in the text. The survey location is indicated in Plates 15.1, 15.2, 15.3 and Figure 15.13.

be used to unravel complex geology in volcano-sedimentary areas. The important condition for success is the presence of conductive saprolite. Studies have shown that saprolite conductivity is a distinct property of many rock types, and in most situations, mafic igneous rocks can be distinguished from felsic sequences by interpretation of AEM data. Identification of different volcanic sequences is often of importance in mineral exploration.

Studies in Canada and France have indicated that AEM techniques are also a useful tool for mapping the lithology and thickness of Quaternary sediments. Besides the mapping aspects, the results can indirectly aid mineral exploration programs by identifying covered valleys suitable for geochemical sampling. The approach is highly cost-effective compared with the presently used shallow reflection or refraction seismic surveys. With further research,

the present limitations in interpretation can be overcome.

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16. Recent Advances in High Sensitivity and High Resolution Aeromagnetics

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ABSTRACT

The need for detailed geologic information for both hydrocarbon and mineral exploration has stimulated demand for high resolution aeromagnetic surveys. In response, new survey instrumentation and techniques have been introduced to meet the demand. The overall resolving power of the aeromagnetic survey is being enhanced in a variety of ways that are fundamentally based on high sensitivity equipment suited to high sample rates or gradient mode operation and well-controlled, closely spaced flight lines at lower survey altitudes when possible. Examples of high resolution data are presented to illustrate particular applications and the benefits of such data relative to conventional surveys.

In addition to total field measurement, a number of systems that measure vertical and/or horizontal gradients are in use and others are under development. These gradient modes of operation can significantly improve the information content of a survey and have relevance to both conventional and high resolution applications. In order to fully realize the advantages of high sensitivity instrumentation in a high resolution mode of operation, corresponding advances in aircraft compensation, platform stability, and accuracy of navigation and positioning must be made.

INTRODUCTION

The aeromagnetic survey has been a popular exploration geophysical method for many years. During the past 40 years, regional mapping has been carried out in many parts of the world to aid both mineral and hydrocarbon exploration. More detailed aeromagnetic data were collected in the 1960s and 1970s as a byproduct of airborne electromagnetic and gamma spectrometer surveys. Recently, a trend has developed towards high sense, high resolution aeromagnetics as a primary exploration method.

An aeromagnetic survey provides a two-dimensional representation of the earth's magnetic field as modified by the underlying geology. The magnetic information may be considered definitive in the sense that surveys flown to the same specifications at different times will produce the same results; however, this is not to say that once an area has been mapped no further information can be expected from subsequent aeromagnetic work. The actual information content of a particular aeromagne-

tic map is a function of several factors; sensitivity of the magnetometer, modes of operation such as total field and gradient, and survey variables such as altitude and line density.

The scope for improving the quality of aeromagnetic data by optimization of these parameters is greatest for mineral-type surveys. Readily available high sense instrumentation can provide high sensitivity data at high sample rates and provide useful magnetic gradient information. The magnetic sources are relatively shallow and reduction in survey altitude from 300 m to 150 m or even 50 m above ground will produce dramatic improvements in resolution. Furthermore, a variety of electronic navigation systems are currently available to provide accurate navigation and positioning information to complement high resolution data collection and compilation.

The aeromagnetic industry has made advances on all fronts. This paper will review some highlights of the currently available magnetometers and associated technology, as well as the various aeromagnetic and gradiometer systems based upon these advances. The advantages offered by these systems and operational considerations related to their effective use are discussed. Survey examples are presented to illustrate particular applications and benefits of such aeromagnetic survey methods.

MAGNETOMETER INSTRUMENTATION

CURRENT SENSORS

In the field of airborne geophysics, three magnetometer types, all introduced in the 1960s, are still at the forefront today. These are the proton free precession, the spin-precession or Overhauser type, and the optical absorption type. Each of these magnetometers is based on a particular physical phenomenon that produces a frequency output that is directly proportional to the total field passing through the sensor. The optical absorption magnetometer is still the most sensitive with a resolution in excess of 0.01 nT; however, the other two types are now approaching the traditional high sensitivity benchmark of 0.01 nT at a one second sample rate.

The free precession proton magnetometer is the most widely used type in operation today. The principal of operation is based on the fact that a proton has a magnetic moment due to its spin and as a result will align itself parallel to an applied magnetic field. If a strong field is applied across the sensor in

a direction transverse to the earth's field, the protons will align themselves with it. When this artificial field is removed the alignment of protons will return to that of the earth's field, and as the spin axes change their alignment they precess at a rate proportional to the earth's magnetic field strength.

The Overhauser magnetometer, also referred to as the spin precession or dual resonance magnetometer, is a derivation of the proton free precession method. If free electrons are added to the sensor liquid, they couple magnetically with the protons and this interaction is particularly strong with the nucleus of nitrogen (nitroxide-free radicals). The advantage provided by this quantum interaction is that the application of a 60 Mhz magnetic field to the sensor can boost the proton precession signal by a factor of up to 5000 (Hrvoic 1973). This gain in effective sensor magnetization permits the polarizing field that deflects the proton spin axes away from the earth's field to be less than a millisecond in duration and measurements may be taken at shorter intervals than in free precession instruments. It is also possible to create a "proton oscillator" with continuous output from the sensor by applying a weak rotating magnetic field that slightly deflects the proton magnetization alignment from the earth's field to maintain the precession signal.

Optically pumped magnetometers are based on electron as opposed to proton spin. Electrons of an atom have different energy states and when a transition between states occurs discrete quantities of energy are absorbed or emitted. The energy of the transition corresponds to a radio frequency spectral line and in the case of helium, cesium or rubidium gas, will result in the absorption or emission of visible light. The process of optical pumping forces all of the electrons to a particular energy level and when complete no more light may be absorbed and the gas becomes transparent. If the gas is then disturbed by a weak alternating magnetic field, the pumped state is disturbed and the gas begins to become opaque allowing pumping to resume. If the frequency of the disturbing field matches the Larmor frequency, a sharp absorption can be detected by a photocell. The helium magnetometer developed by Arco Sinclair and subsequently by Questor uses a field sweep technique to track the Larmor frequency. The cesium magnetometer developed by Varian and now produced by Scintrex Limited is a self-oscillating device that uses a modified output signal from the photocell to create the alternating magnetic field in the sensor. By either technique, the output of the device is a continuous Larmor frequency proportional to the total magnetic field at the sensor.

POSSIBLE FUTURE SENSORS

The three types of currently used magnetometers are all total field instruments. Interestingly, newer mag-

netic sensor types include several vector devices; the SQUID (superconducting quantum interference device) magnetometer is one of them. These sensors measure changes in magnetic flux through a superconducting loop with a potential resolution in the order of 0.0001 nT. The loop required is small and gradiometer configurations based on six or more SQUIDS machined in a single block about 10 cm in size have been attempted. SQUID magnetometers have been applied to ground geophysical surveys but regular airborne operation as a magnetometer is still in the distant future; however, the recent discovery of higher temperature superconducting ceramics may accelerate research and development activity. Details of the SQUID and its application to a variety of geophysical methods are reviewed by Weinstock and Overton (1981).

Another vector magnetometer that has seen airborne and spaceborne use is based on the magnetic fluxgate. For the MAGSAT satellite, NASA undertook the development of a vector magnetometer based on the ringcore fluxgate (Acuna 1980). It was launched in June 1980 and operated in conjunction with a scalar optically pumped magnetometer. The resolution of the instrument was $\pm .5$ nT, not high sensitivity, but higher resolution from fluxgate sensors is possible. The ringcore fluxgate design offers lower noise and improved stability and has been adapted by IFO Limited to produce an airborne vector magnetometer with a resolution on each component of 0.1 nT.

Vector magnetometers are commonly used for ground-based geophysical operations where the instrument can be held stationary. Airborne application of vector devices is hampered by the moving platform and the limitation of maintaining a directional reference for the magnetometer. The incentive to measure the three vector components of the magnetic field lies simply in the fact the direction of the field is an added independent interpretive parameter that is useful in identifying both the location of the magnetic source as well as some of its physical attributes.

The principal difficulty in using a vector magnetometer to provide both vector and scalar information lies in extremely fine tolerance needed for vector alignment. This can be simply appreciated by noting that a fluxgate element aligned with a magnetic field of 50 000 nT would sense a change of 0.1 nT with an angular movement of only 0.001 degree. An alternative approach to obtain both scalar and vector magnetic information currently lies in the combined operation of vector and total field instruments such as the method under development at Airmag Surveys Incorporated. Fluxgate sensors were orthogonally aligned on a plate that could be oriented via a two-axis servo system to maintain a null response in the fluxgates. The magnetic field direction is thereby monitored as the normal to the plate. This style of servo-driven platform has been in use

as part of airborne sensors for many years as a means of sensor alignment and certainly has the potential for precise angular measurement. The limiting factor for this or the three-axis fluxgate method of resolving field direction is the subsequent step of determining the angular position of the airborne platform for consistent vector reference. In spite of this limitation, it is likely that in the near future aeromagnetic surveys may include vector information together with the traditional scalar total field measurement.

LARGER FREQUENCY MEASUREMENT

The optically pumped and proton precession instruments produce a sinusoidal signal output whose frequency is proportional to the total magnetic field at the sensor. The relationship between this frequency and magnetic field strength is shown in Table 16.1.

The resolution of these devices is fundamentally governed by the signal-to-noise level of the sensor output, a frequency which must be measured with great precision. Recently, there have been some new frequency measurement techniques introduced that can provide very high resolution as well as a level of noise rejection as part of the frequency measurement. Frequency may be measured by two basic methods. One may measure the number of cycles completed over a known period of time or alternatively one may measure the time required to complete a given number of cycles. Various measurement schemes are illustrated in Figure 16.1.

The first method, event counting (Figure 16.1a), has the limitation that if the frequency is low the resolution of the measurement is low unless the measurement time period is long. If frequency f is to be determined within a one second interval, the associated uncertainty of 1 cycle limits the resolution of the measurement to $1/f$. Thus to achieve a resolution of 0.01 nT, in a field of 50 000 nT within a 1 second measurement, the input frequency must exceed 5 MHz. The precession output would only be 2128 Hz and even the helium sensor with an output of 1.4 MHz would fall short of the threshold. Equipment designs have employed frequency multiplication methods to circumvent this threshold and multiplication factors as high as 2000 have been applied to proton precession instruments to attain the necessary measurement resolution. The frequency multi-

plication process is noise sensitive and with larger multiplication factors, damping in the sense of reducing the responsiveness to rate of change of input frequency must be increased, an undesirable limitation.

The alternative measurement technique, period measurement (Figure 16.1b), appears to be the most widely used at present. The basic resolution of a period measurement is tied to the resolution of the measurement clock and is independent of the input frequency as long as the period to be measured is shorter than the measurement interval. A traditional limitation of this method was related to the uncertain timing of the measurement, how many periods could be measured within the time available. Taking the proton precession example where a 50 000 nT field produces 2128 Hz; to allow for a ± 25 000 nT variation a frequency range of 1 to 3 kHz must be provided for. To base all measurements on the 1 kHz limit would mean that at the mean level of 2 kHz the measurement would be determined within 0.5 second and half the potential resolution of the system wasted.

Several permutations of the period measurement technique have been recently introduced. A digital period measurement technique has been developed that ensures full usage of the sensor output (Hogg 1985). Measurements are initiated and terminated on a prescribed uniform time interval (Figure 16.1c). The device counts the full number of wavelengths within this interval and also measures the fractional segments at the start and end of the interval, thus providing a fractional measurement of the number of wavelengths. The system utilizes an 81 MHz clock reference and can potentially resolve 0.0006 nT in a one second measurement period independent of magnetometer frequency output. The sample rate is typically five readings per second but is not limited other than by the practical provisions of recording the output.

Digital signal-to-noise enhancement as part of the measurement process is a new development in magnetometer design. The output signal from a magnetometer is not pure and if the fundamental wavelength due to the magnetic field is say T seconds, it can be expected to have an added error term eT . This error term is random in the sense that the sum of a sufficiently large sample of eT approaches zero. It is readily recognized that the impact of eT is reduced by a longer measurement period encompassing more events and hence more eT . This is simply a filter operation that assigns equal weights to 'N' independent observations. The greater 'N' becomes, the larger the filter operator becomes and a lower bandpass results. Specially designed digital filters can be substituted for the equal weights to provide improved noise rejection within the same passband. The sample rate is particularly important to this process. If a magnetometer reading is made only several times per second, the noise component is

TABLE 16.1: RELATIONSHIP BETWEEN LARMOR FREQUENCY AND MAGNETIC FIELD STRENGTH.

nT = frequency/k		
for optically pumped	helium	k = 26.024
	rubidium	k = 4.667
	cesium	k = 3.498
proton (free precession and Overhauser)		k = 0.043376

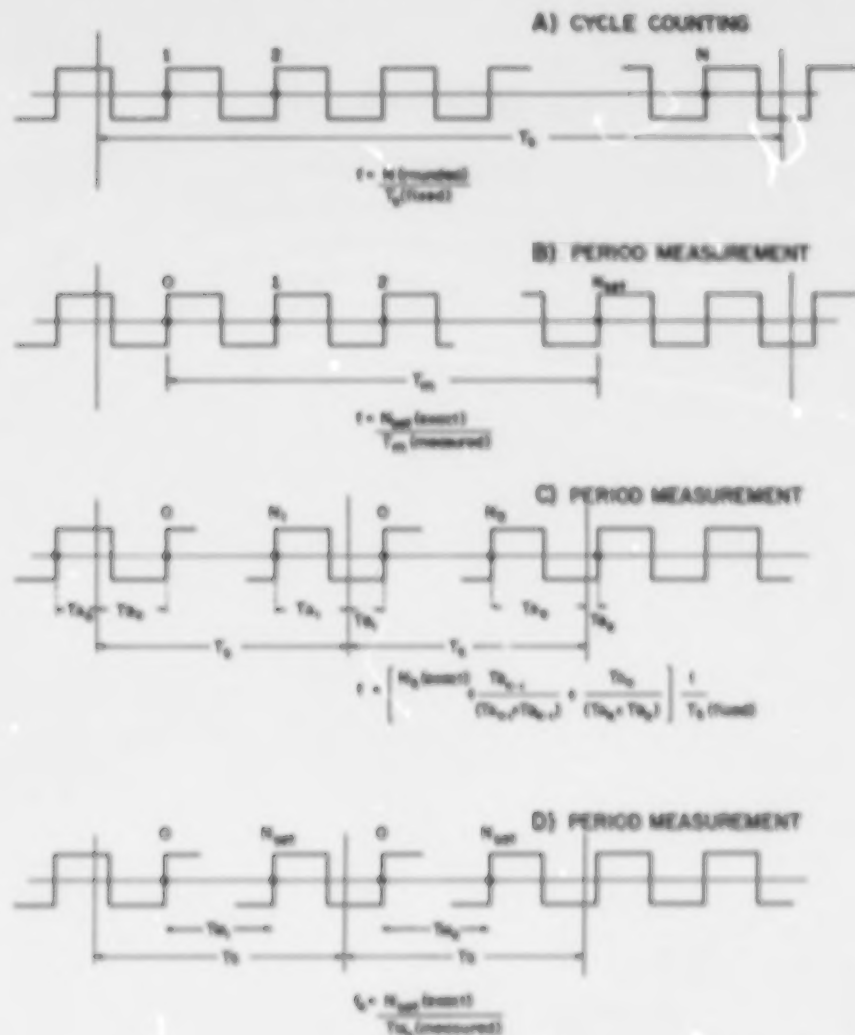


Figure 14.1. Frequency measurement techniques used for magnetometers. The two fundamental methods are a) cycle counting and b) period measurement; c) and d) are recent variations on the period measurement method.

aliased with the geologic or signal components and the noise cannot be filtered out without distortion of the signal. If the sample rate is high, aliasing is minimized and the noise component can be reduced with minimal impact on true signal. The filtering process is best done in real time to avoid recording excessive amounts of data.

Picodas and Scintrex Limited have developed a magnetometer frequency measurement device that features such digital filtering as an integral part of the measurement. Period measurements are made using an 18.4 MHz reference, 100 times per second. This string of independent measurements is then digitally filtered with an operator whose passband is selectable. Although the resolution on each of the initial 0.01 second measurements is one

part in 184 kHz (about 0.27 nT), the resolution of the filtered output for say a 1 second sample is increased to about 0.0027 nT.

GRADIOMETER OPERATION

A gradiometer requires more than the parallel operation of two magnetometers. In the earlier discussion of frequency counting techniques, it was pointed out that 0.01 nT typically represents a measurement resolution of one part in five million. Clocks with this short-term stability are not available and the only practical method to obtain consistency of time reference between two or more magnetometers is to share the same clock. This ensures that whether one is measuring cycles per second or seconds per cycles, errors in time measurement will be

applied equally to both sensors and therefore not affect the gradient measurement.

The determination of a magnetometer's true sensitivity or noise level is difficult if for no other reason that the magnetometer represents a frequency measuring device whose resolution exceeds that of conventional electronic test equipment. A practical evaluation of a magnetometer is best made against itself and this is simply done with sensors properly integrated into a gradiometer system. The performance of the frequency measurement part of the system can be easily evaluated by feeding the same synthetic or real signal into both counters simultaneously. They both see the identical signal, and the gradient by definition should be zero. A sample of such a test carried out by Aerodat is illustrated in Figure 16.2. The comparative noise level of the sensors or potential noise level of a gradiometer system is achieved by providing real input from two stationary but independent sensors. A fixed gradient may be expected between the sensors but any deviation from constant level is a direct measure of the noise. A sample of such a test result using Scintrex cesium sensors is illustrated in Figure 16.3. The noise level from the counters alone (see Figure

16.2) is about 0.005 nT. It is also clear that the noise is independent of the rate of change of the magnetic field as evident in the central section of the profile where extremely rapid variations have been introduced. With actual gradient data from two independent sensors (see Figure 16.3), the noise grows to about 0.015 nT. The difference, 0.01 nT, is a measure of the actual performance of the cesium sensors.

AIRBORNE OPERATIONAL CONSIDERATIONS

In order to realize the benefits of the high sensitivity magnetometers, considerable attention must be given to the aircraft as an operating environment of the sensor. It will contain magnetic and electromagnetic noise sources and will subject the sensor to vibration and pitch, roll and yaw motions. These operational liabilities are not new to aeromagnetics but the need to reduce their potentially detrimental effect on data quality has become more acute.

SENSOR PERFORMANCE

Proton precession magnetometers require that the spin axes of the protons be aligned at right angles to

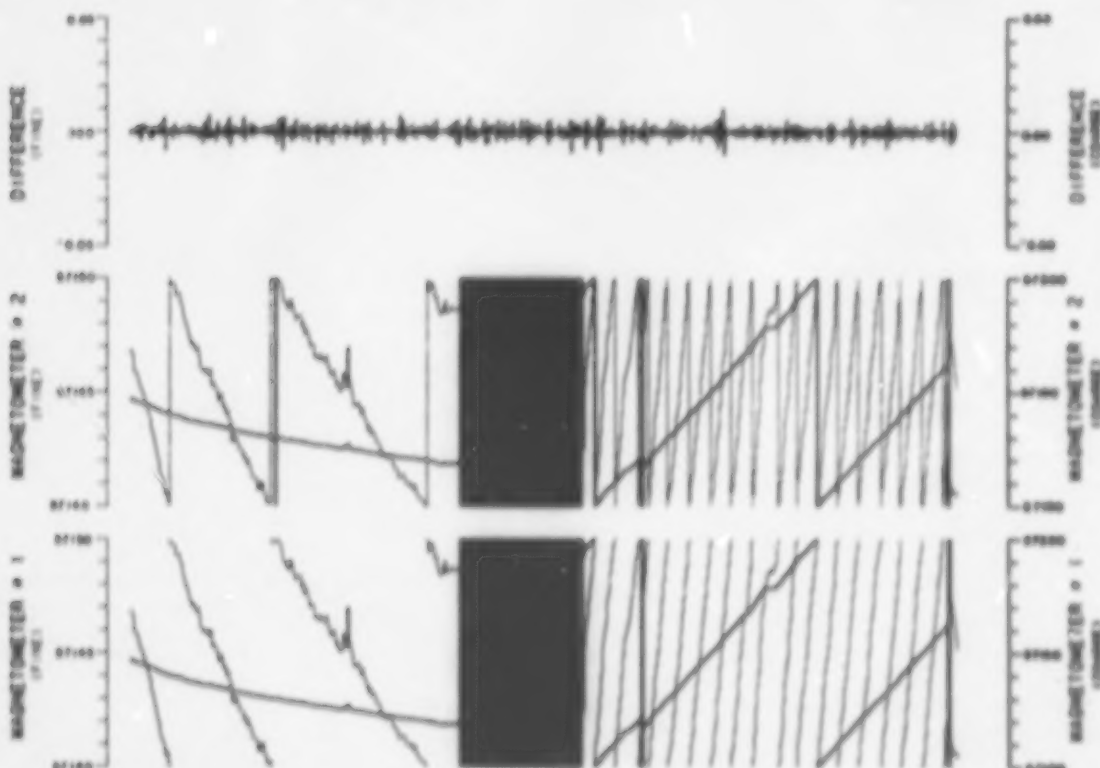


Figure 16.3. An artificial signal from a modulated signal generator is fed to both inputs of a gradiometer console operated at a 0.25 second sample rate. The output profiles are labeled magnetometer 1 and 2. The difference profile is insensitive to the rate of change of the synthetic signal, but does indicate a basic measurement error of about 0.005 nT.

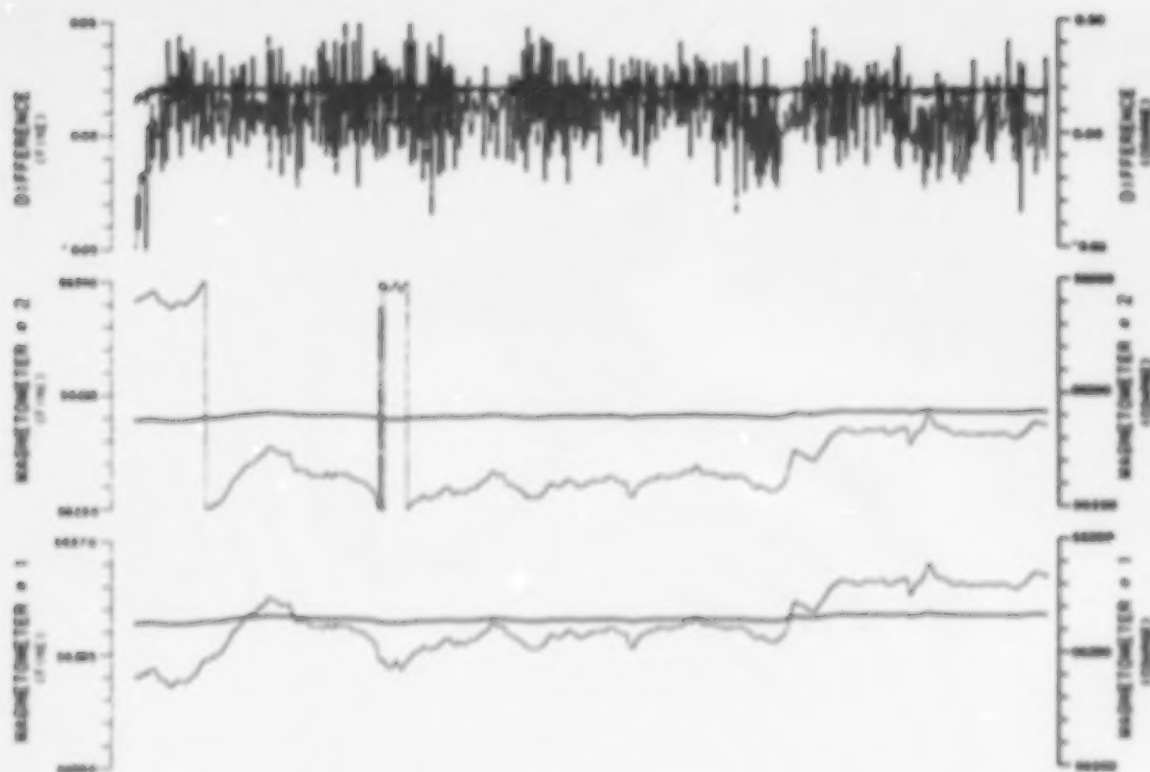


Figure 16.3. The same gradiometer console as used in Figure 16.2 is provided with signals from two different but stationary cesium sensors. The shift in the base level of the difference channel is expected due to the different total field levels at the sensors; however, the increase in high frequency activity relative to Figure 16.2 is indicative of the noise associated with the sensors.

the magnetic field direction for maximum signal strength. Variations up to 45° or more are acceptable and this limitation does not represent a serious operational restriction. More serious is high frequency orientation changes due to vibration that can modify the precession signal and produce noise. Optically pumped magnetometers have a similar basic alignment requirement that the magnetic field be aligned at 45° to the optical axis of the sensor for maximum signal. Variations of up to about $\pm 25^\circ$ can be tolerated; however, this range is small enough to be an operational limitation. Multicell sensors have been developed to increase this operating range but it is a technically difficult process and has not been widely adopted as a solution.

In addition to the basic signal requirements, orientation can lead to a small but significant error on optically pumped sensors. This error not only varies from one type of optically pumped sensor to another but between sensors of the same type. Figure 16.4 illustrates the orientation error for a cesium airborne sensor. The curves were measured at a magnetic test site established by Sciencetex Limited near Toronto. The sensor to be monitored is placed in a particular orientation in the earth's magnetic field and rotated

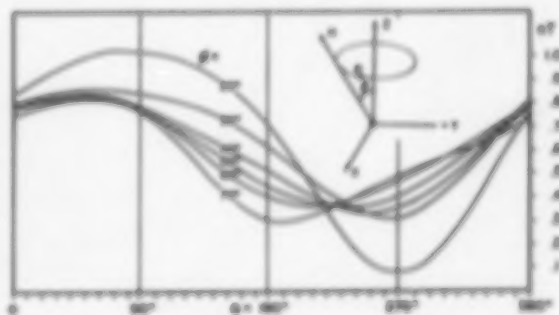


Figure 16.4. Example of the orientation error of a cesium sensor. The profiles are generated by measuring the difference in output between a sensor rotated in the earth's magnetic field and another held stationary. These curves will vary from sensor to sensor.

around a chosen axis. A second stationary sensor is operated in parallel and the difference in output of the two sensors provides a measure of the orientation error. This particular presentation illustrates an error curve for a full 360° rotation about the sen-

nor's optical axis with the angle between the magnetic vector and the optical axis ranging from 20 to 70° in 10° increments. For the sensor illustrated, errors up to 0.03 nT per degree attitude change of the sensor could be encountered; however, these more active error zones can be largely avoided by choice of sensor orientation for a given survey flight line direction and magnetic field inclination.

A method for avoiding this error as well as the general limitations of sensor alignment is to employ a sensor orientation system. The most sophisticated of these is a two-axis gimbal system, the ASQ-502/504 developed by CAE Electronics Limited. The principal user of the system is the military for ASW (anti-submarine warfare)-equipped aircraft. The system employs two orthogonal coils rigidly coupled to the magnetic sensor. These are driven with an alternating current to produce a rotating magnetic reference. If the plane of this rotating vector is not orthogonal to the earth's field, it will be visible to the magnetometer and its amplitude and phase can be used to drive a servo system to restore orthogonality. By this means the sensor can be dynamically maintained in fixed relationship with the earth's magnetic field vector. Such orientation systems are typically more expensive than the magnetometers that they support, but they are now a part of some of the more sophisticated airborne magnetometer and gradiometer systems such as the OSC Queenair and the Kenning Navaho gradiometer systems.

GRADIENT TOLERANCE

Mineral-type magnetic surveys at low level can encounter very strong magnetic anomalies. Over iron formations the field may vary by ± 50 percent from ambient, and the associated magnetic gradients are high. If the gradient within the magnetic sensor is sufficiently large, the magnetometer does not receive a consistent response from different regions within the sensor and the output signal is degraded and ultimately will be lost altogether. Sensor size is a key factor hence the small optically pumped sensors have a considerably higher gradient tolerance than the larger proton precession devices. The advantage is not entirely without liability; a strong magnetic anomaly that makes gradient tolerance a concern will also modify the inclination and declination of the local total magnetic field to the extent that orientation limits may be exceeded without a means of automatic sensor alignment.

AIRCRAFT NOISE AND COMPENSATION

The survey aircraft is a source of magnetic noise arising from permanent and induced magnetization as well as from eddy currents induced in the conductive airframe or skin. A towed bird sensor configuration offers a solution by simply separating the sensors adequately from the source of the noise. Although apparently straightforward, problems are in-

troduced by the long signal cable, vibration of bird and tow cable, and wandering of the bird which may lead to orientation errors.

Most aeromagnetic contractors prefer the on-board as opposed to towed sensor for increased predictability of operation and security of hardware. The sensor is rigidly mounted to the aircraft as far away as possible from the engines and other major magnetic sources. The magnetic anomaly of the aircraft is then measured and by either an analog or digital process removed from the measured total field.

Magnetic compensation of an aircraft is not new, and various methods with different levels of sophistication have been in use for decades. The current state of the art appropriate to high sensitivity surveying compensates for permanent, induced, and eddy current magnetic effects. The first devices were developed for military ASW use but have since been adopted for aeromagnetic survey use. Analog and combined analog/digital devices are manufactured by CAE and a fully digital device developed by the National Aeronautical Establishment (NAE) of the National Research Council Canada and is available from RMS Instruments.

The principal of operation for all of the devices is similar and based on a model developed by Leliak (1961). The basis of the model is illustrated in Figure 16.5. An XYZ orthogonal co-ordinate system is tied to the aircraft. The projection of the earth's field on this co-ordinate system will change with the pitch, roll, and yaw of the aircraft and the components H_x , H_y , and H_z are monitored by means of three fluxgate magnetometers aligned with the axes. The permanent magnetization vector P is fixed relative to the XYZ co-ordinates. The induced magnetization vectors I_x , I_y , and I_z have a fixed directional relationship with X , Y , and Z but their scalar amplitude is proportional H_x , H_y , and H_z , respectively. The influence of the eddy currents also leads to three vectors E_x , E_y , and E_z that are also of fixed direction relative to XYZ but their scalar amplitudes are proportional to dH_x/dt , dH_y/dt , and dH_z/dt , the time derivatives of the total magnetic field components. In all, there are seven error vectors; one "perm", three "induced", and three "eddy" and as vectors, 21 terms are required for their definition in the XYZ co-ordinate system. These 21 terms or unknowns are derived from calibration flight maneuvers designed to generate an identifiable error signal that may be analysed to calculate the terms. With some mathematical finesse the number of terms may be reduced to 18 or even 16 and in certain relatively clean aircraft, adequate compensation may be achieved with as few as nine terms.

In both the CAE and RMS/NAE systems, a computer is utilized to identify the various correction terms. The principal difference in approach is that CAE generates a magnetic field in the vicinity of the sensor that cancels the predicted error component,

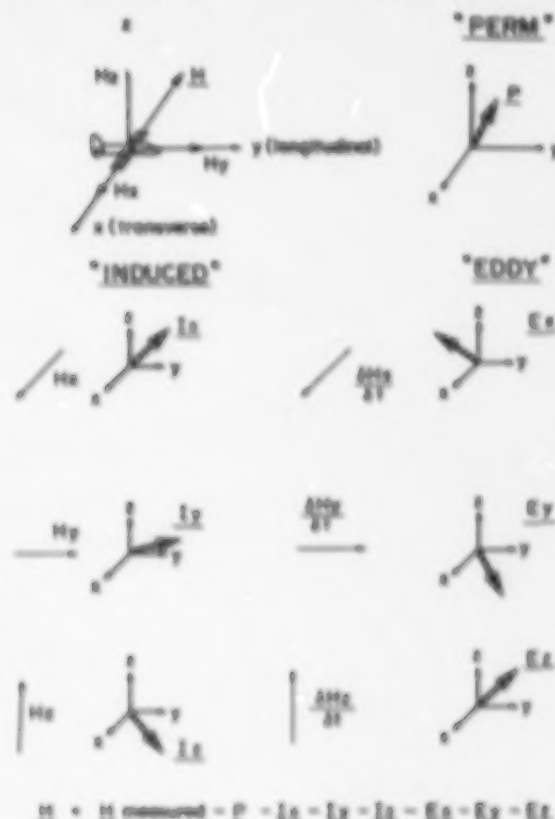


Figure 14.5. A conceptual illustration of the elements of the basic magnetic interference model used for aircraft compensation. I_x , I_y , and I_z as well as their time derivatives are measured by a triad of fluxgate sensors rigidly attached to the aircraft. The **PERM**, **INDUCED**, and **EDDY** vectors are predicted by the model and applied as corrections to the measured total magnetic field.

whereas the RMS/NAE approach is to provide a digital correction to be applied to the raw measured value. This fully digital approach does offer some advantages in gradiometer configuration by avoiding potential compensation cross talk between sensors closely spaced on an aircraft.

AIRBORNE MAGNETOMETER AND GRADIOMETER SYSTEMS

The traditional realm of the high sensitivity magnetometer has been in hydrocarbon exploration where depth to source is measured in kilometres. Anomalies arising from this depth may be weak but their wavelength may also be measured in kilometres and magnetic anomalies of fractional nT amplitude may be successfully mapped and interpreted.

In mineral exploration, the depth to magnetic source may be as little as 30 m and anomaly amplitudes range from fractional nT through thousands of

Figure 14.6. (opposite) A helicopter survey example from the Mount Stokes area of Québec published by the Geological Survey of Canada. Two cesium sensors separated by 3 m were towed at 45 m above ground with a nominal line spacing of 100 m. A radar navigation system was used for flight path positioning. The total field is presented in (a) and the measured vertical gradient in (b). For comparison, the calculated vertical gradient is presented in (c).

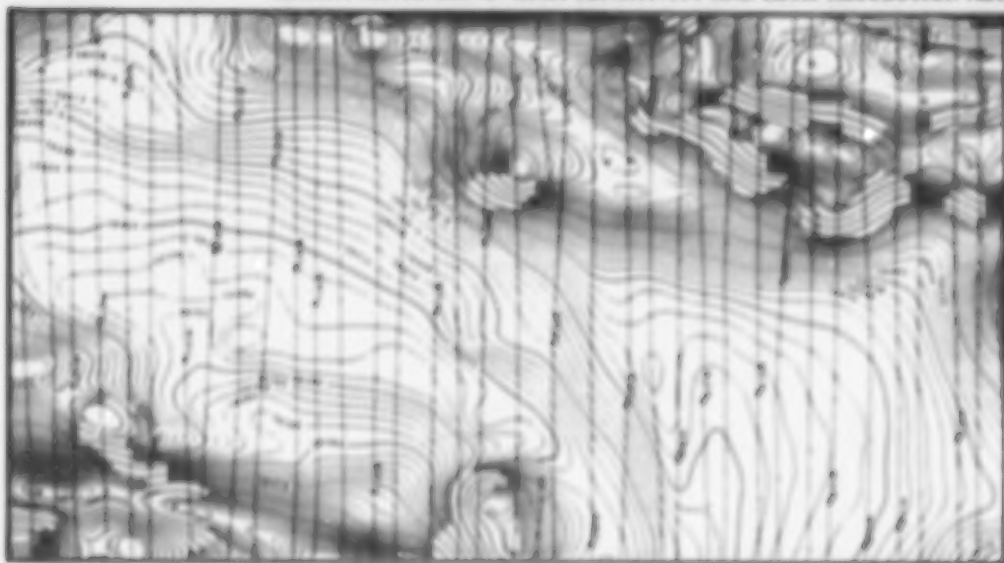
nT. The small amplitude features are often superimposed on a very active background and the benefits of high sensitivity instrumentation are indirect.

One such benefit arises from potential trade-off from high sensitivity to high sample rate. An instrument capable of measuring 0.01 nT at 1.0 second sample rate can also provide 0.1 nT at a 0.1 second rate. Visible improvement in anomaly resolution can be gained with sample interval reductions down to about 0.2 of the height above source. At a survey elevation of say 100 m and an aircraft speed of 180 km/hr (50 m/sec), a sample rate of 0.4 second is appropriate.

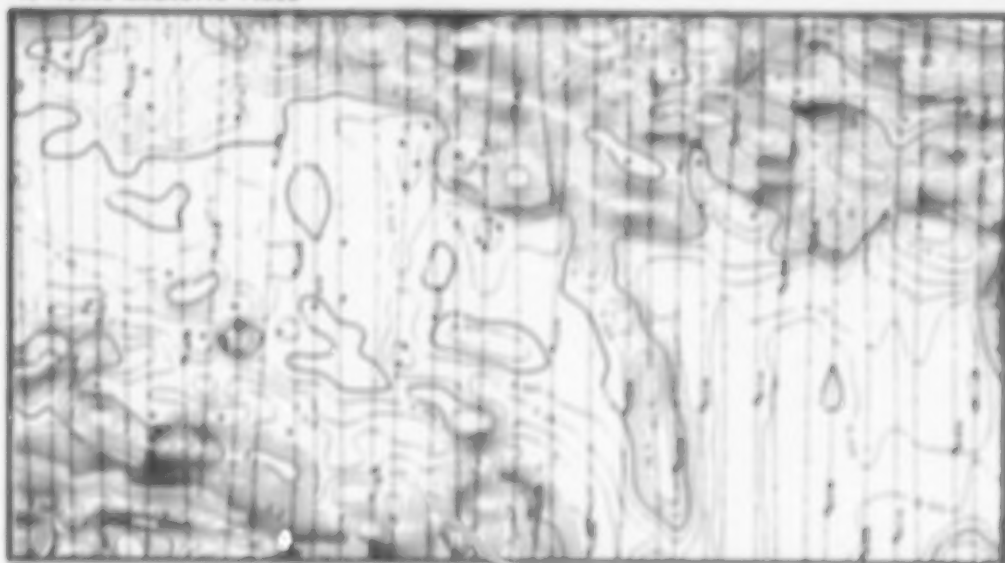
The more interesting benefit is to utilize the high sensitivity to resolve magnetic gradients over a relatively short baseline. The airborne measurement of magnetic gradients is not a new concept (Hood 1965; Slack 1967); however, the variety of systems offered, and in particular those configured for mineral exploration, has grown rapidly over the past few years. Fixed wing and helicopter systems that measure vertical, longitudinal, and transverse gradients are in current operation. The principal benefits of these gradient configurations are several:

1. Diurnal variations of the earth's field will appear equally to the sensors operated in gradient mode. The longitudinal, transverse, or vertical gradient measurement may be integrated to produce a total magnetic field map free of diurnal variation. Such a calculation is not perfect in that the longer wavelength regional information is not resolved by the gradiometer, but a useful representation of shorter wavelength, residual magnetic anomalies, may be obtained economically in areas of extreme diurnal activity.
2. One of the most popular benefits of gradient measurement and presentation is the enhancement of weak but shallow anomalies. A small inflection on the flank of a larger total field anomaly may become a distinct vertical gradient feature. An example that allows comparison of total field and vertical gradient data is provided in Figures 14.6a and 14.6b.

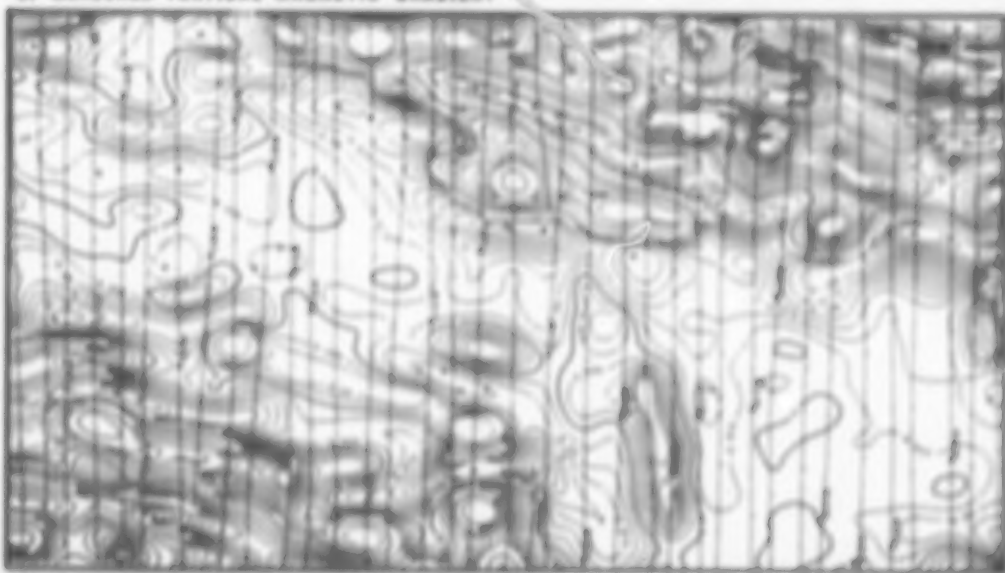
It is a matter of some debate as to whether this enhancement of weaker total field anomalies warrants vertical gradient measurement. Digital map enhancement processes such as first and second vertical derivative calculation from total field data are technically sound and well proven over many years of use. Furthermore, processes such as apparent mag-



A) TOTAL MAGNETIC FIELD



B) MEASURED VERTICAL MAGNETIC GRADIENT



C) CALCULATED VERTICAL MAGNETIC GRADIENT

capability mapping provide a similar enhancement in a form that is perhaps more geologically meaningful. If the quality of the total field mapping is good and visual enhancement of features is the final objective, digital computation is completely appropriate. On the other hand, if the geology and therefore the magnetic field is complex to the extent that accurate total field mapping is difficult, then measurement of the vertical gradient is definitely warranted. The quality of the total field map and any subsequent map enhancement may be limited by survey conditions such as rugged terrain where flight level will be variable, or excessive diurnal variations, or difficult flight track recovery conditions. It is also possible that even without these survey limitations, the geology and related magnetic field may be sufficiently complex that accurate total field mapping is difficult. Under these conditions, measurement of the vertical gradient is definitely warranted. Also, should a subsequent interpretive process be designed to utilize the vertical gradient data, it should be a directly measured rather than derived parameter. To illustrate the difference, Figure 16.6c presents a vertical gradient map calculated from the total field map (Figure 16.6a) that may be compared with the measured vertical gradient map (Figure 16.6b). Fine detail is evident in the measured gradient that is not evident in the calculated gradient.

- Perhaps the most innovative use of a gradiometer configuration is to use the horizontal magnetic gradients to improve the two-dimensional representation of the total magnetic field. The value of the information is apparent in the content of the basic definition of a contour line on a map: it is the locus of values of equal magnetic intensity. Along the local strike of the contour the horizontal gradient is zero and normal to the strike it is a maximum. Figure 16.7 illustrates how the horizontal gradient components relate to the strike direction of the contour. This fundamental information of the contour strike direction at the flight line can be used in a variety of ways to improve the interpolation of aeromagnetic data between flight lines. An example of such an application by Hansen (1983) is presented in Figure 16.8. The greatest improvements in interpolation are evident at locations A and B where the magnetic strike direction is not perpendicular to the flight line direction.

HIGH RESOLUTION SURVEYS

SURVEY ALTITUDE

In most mineral exploration environments, the depth below surface to magnetic source is less than 100 m. A change in survey altitude from say 300 m to 100 m reduces the height above source by 50 per-

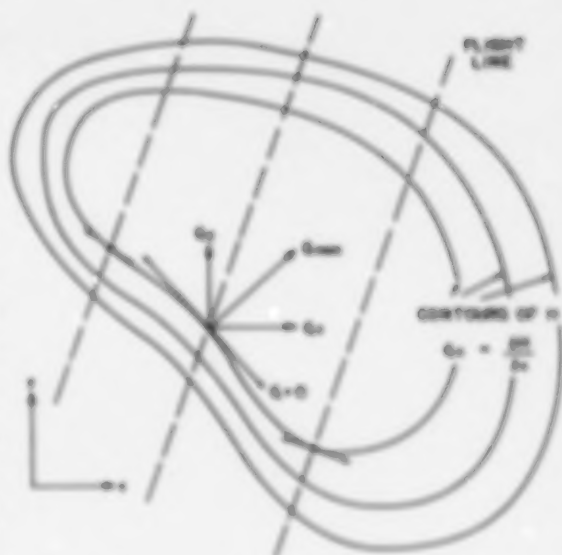
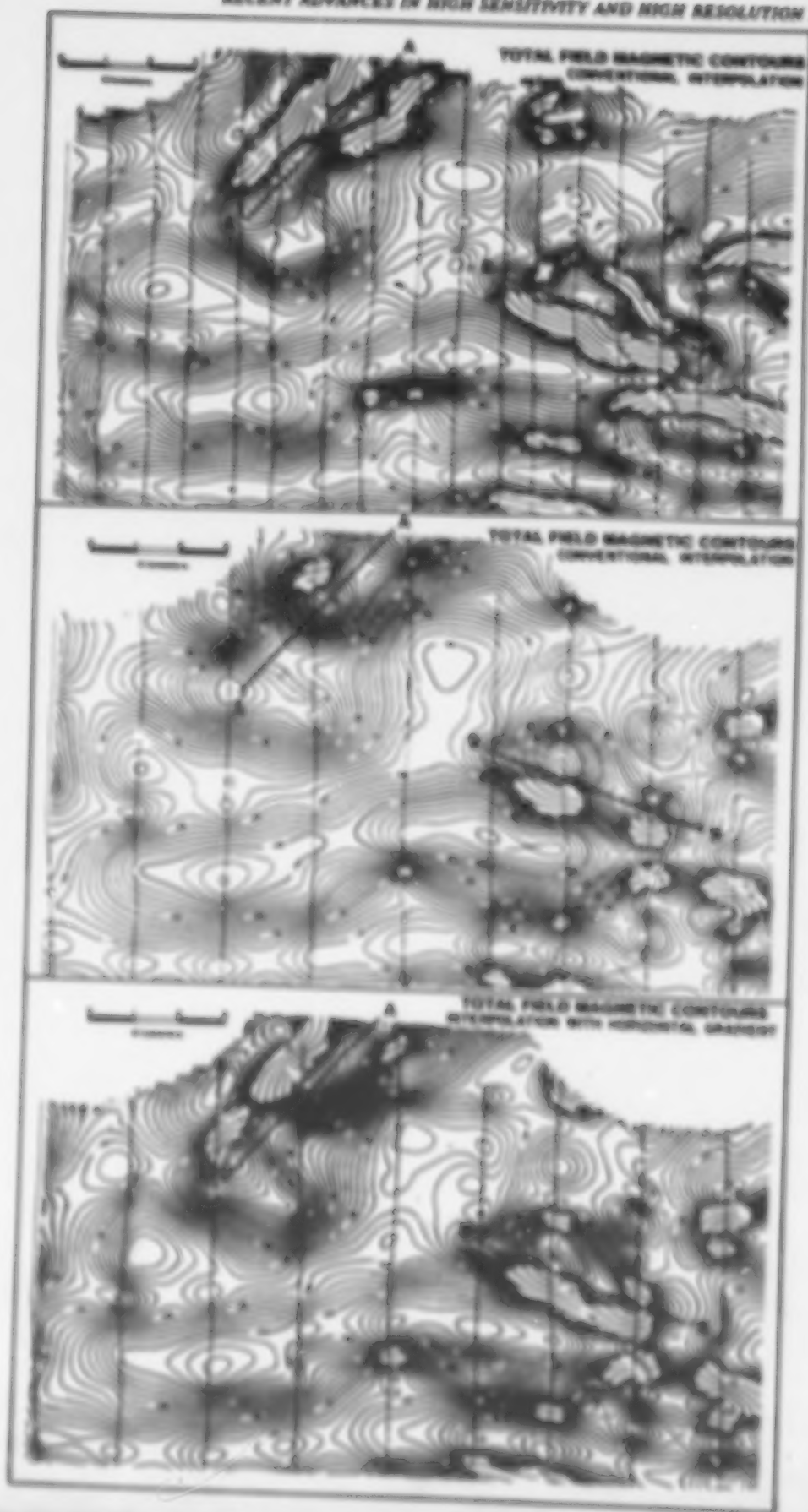


Figure 16.7. An illustration of the relationship between total magnetic field contours and the horizontal magnetic gradient. The direction corresponding to zero horizontal gradient is by definition tangential to the contour lines. Measurement of this direction on each flight line can improve interpolation from line to line.

cent and a gain in anomaly amplitude from four to eight times can be expected. Figure 16.9 illustrates the total field and vertical gradient response to three vertical prisms of widths varying from 1 km to 1 m. The associated susceptibilities were selected simply to provide similar amplitudes for presentation. At a height of 300 m above source, neither the total field nor vertical gradient profile, visually resolve the two smaller features. At 150 m, the vertical gradient provides a weak but recognizable distinction. At 100 m and 50 m, both the vertical gradient and total field profiles clearly resolve all three sources. The vertical gradient without doubt improves resolution at a given survey altitude but where practical, a significant reduction in survey height above geological source will provide the greatest increase in resolution.

Figure 16.8. (opposite) A horizontal gradiometer survey example provided by Terra Lines Incorporated. The survey flown in 1983 was at an average terrain clearance of 450 m and nominal line spacing of 1 km. The horizontal gradient was measured using wingtip probe precision sensors. A conventional total field interpolation of 1 km data is shown at the top. The control map is the same but only every second line has been used. The bottom map also uses every second line but employs the horizontal gradient data to aid interpolation. In the vicinity of A and B, the lower presentation is more accurate than the control map when compared to upper compilation employing more flight lines.



SURVEY LINE DENSITY

Appropriate survey line spacing is a function of survey height above magnetic source. Any increase in anomaly resolution achieved by lower flying altitude must be accompanied by a decrease in line spacing to usefully resolve the lateral variations of the collected data. As part of the map-making process, data collected along profiles is interpolated onto a regular grid for contouring and various forms of digital enhancement. Although many different gridding routines exist, they all must interpolate between the measured observations and will suffer from under-sampling.

Figure 16.10 presents an example of this limitation. Three narrow linear anomalies of different strike direction have been modeled and the proper contour rendition is shown. Different flight line spacings have been created by extracting profiles at different intervals and applying a common cubic (also referred to as bicubic) spline interpolation technique. Anomalies with a strike direction perpendicular to the flight lines are relatively well rendered at even very wide spacings but as the strike angle decreases from 90°, degradation sets in rapidly with increasing line spacing. This presentation illustrates the general rule of thumb that the line spacing, for quality

aeromagnetic mapping, should not exceed twice the height above source. As a matter of interest the presentation at the bottom right of Figure 16.10 has employed horizontal gradient data to improve the interpolation. The results at S=3D for the small strike angle feature are comparable to the rendition at S=2D without the benefit of the extra gradient information.

NAVIGATION AND POSITIONING

The traditional path recovery technique using tracking film or video is quite acceptable at survey altitudes of 150 m or greater above magnetic source as long as topographic relief is moderate and photo detail adequate for the task. At lower altitudes in more rugged terrain, the aircraft speed may vary significantly and although the accuracy of the picked points may be acceptable, the interpolation between such fixes may be inadequate.

The required accuracy of position is a function of height above source in the same sense as line spacing. To illustrate the relationship, a sample from an actual survey is presented in Figure 16.11a. The positioning of the data in the illustration is reasonable but not perfect. In Figures 16.11b and 16.11c, the position of the data along track has been deliber-

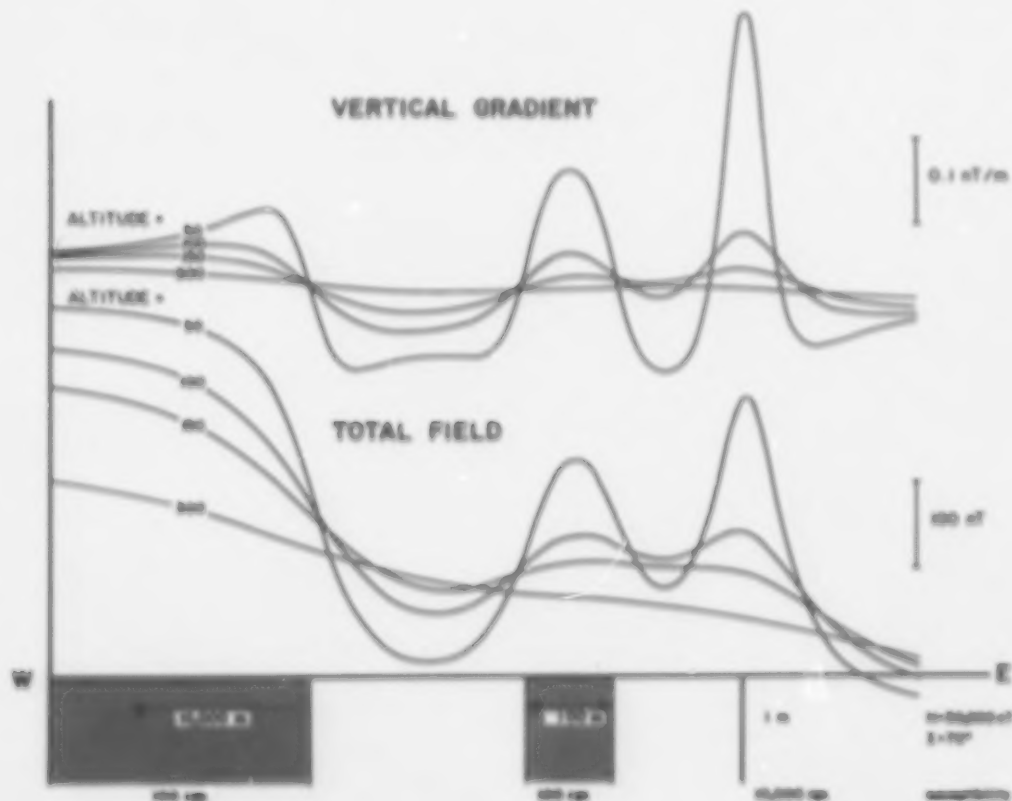


Figure 16.9. Model responses of total field and vertical gradient for three vertical prisms.

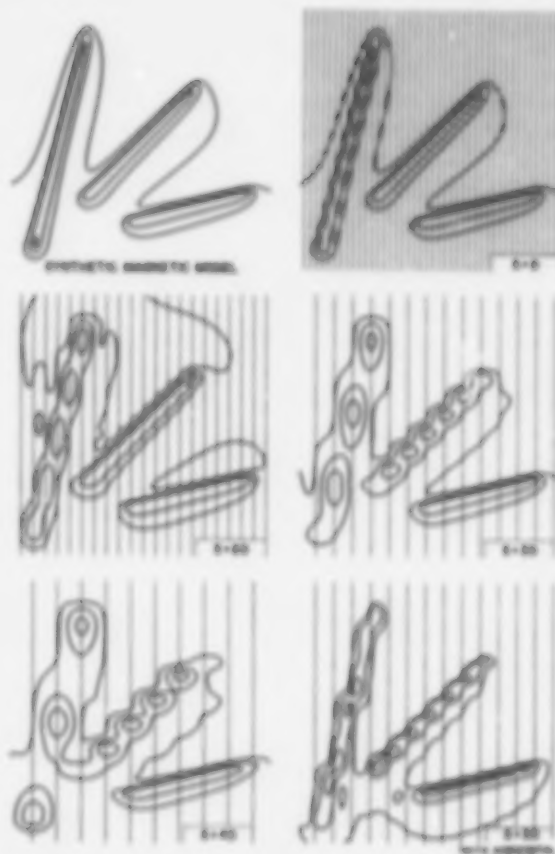


Figure 16.19. A simulation of the effect of line spacing 'E' as a function of survey height above magnetic source 'D'. In one example, the horizontal gradient data has been used to aid interpolation.

TABLE 16.2: ELECTRONIC NAVIGATION SYSTEMS.

RADIO (DIRECT DISTANCE MEASUREMENT)			
Type	Frequency	Accuracy	Range
Radar	3.5 GHz	5 - 10m	50 - 80 km
UHF	0.4 GHz	10 - 20m	100 - 150 km
(GPS Satellite)	1.4 GHz	30 - 50m	Global
Loran C	100 KHz	30 - 500m	2500 km
Omega	10 KHz	300 - 3000m	9000 km
DOPPLER (VELOCITY MEASUREMENT)			
Single Integration		Accumulation Error (Near Linear) 2 m/min	
INERTIAL (ACCELERATION MEASUREMENT)			
Double Integration		Accumulating Error (Non linear but predictable periodicity) 2 m/min	

ately shifted by 10 percent and 20 percent of the line spacing. With an arbitrary error of 10 percent introduced, the general quality of the presentation is not greatly altered, in fact in sections of the map the herring bone pattern is reduced suggesting that errors in the order of 10 percent of the line spacing probably exist in the original compilation. With the error increased to 20 percent, a visible degradation is readily apparent. The actual line spacing in the example is 100 m nominal at a height above source of about 70 m. The scale is not significant to the demonstration in that the relative dimension could be 1 km and 700 m, respectively. The example illustrates that the accuracy of data position should be better than 10 percent of line spacing or by previously discussed depth to line spacing ratio the positional error should be less than 20 percent of the height above source.

At survey altitudes below about 150 m, electronic positioning can contribute significantly to the proper positioning of acquired data. A wide variety of systems is in current use by the airborne geophysical industry and are outlined in Table 16.2. The systems are grouped into three categories: radio, doppler, and inertial. The radio systems make direct distance calculations and the positional error at any point is independent of the next. With the exception of satellite systems, the accuracy of the systems in general is proportional to their operating frequency. Doppler systems measure velocity and derive distance travelled by means of integration. As a result, errors can accumulate and the derived position of the aircraft will appear to drift. The drift in doppler systems is often near linear over typical survey distances and ties to known locations can be used to perform a drift correction after the flight. Inertial systems measure aircraft acceleration and derive relative position by means of a double integration. One component of inertial system's drift may be near linear but a larger error termed the Schuler effect introduces a sinusoidal error, kilometres in amplitude, with a period of 184 minutes. With accurate positional updates every 10 to 15 minutes, the linear and nonlinear drift can be corrected after the flight.

The accuracies presented in Table 16.2 are typical from the experience of the author and variations can be expected. Without question, the radar and UHF radio systems provide the highest accuracy but have the logistic complexity of establishing and maintaining ground beacons. The Loran-C method uses a government-operated transmitter network primarily for shipping and if the survey is in a coastal region good coverage can usually be expected. The doppler and inertial system need a second method of positioning to provide accurate flight line positioning. This may simply be visual path recovery or a secondary radio positioning system. For example, Geotrex together with Nortech assembled an integrated navigation system for a survey off Atlantic Canada. A GPS (global positioning system) satellite

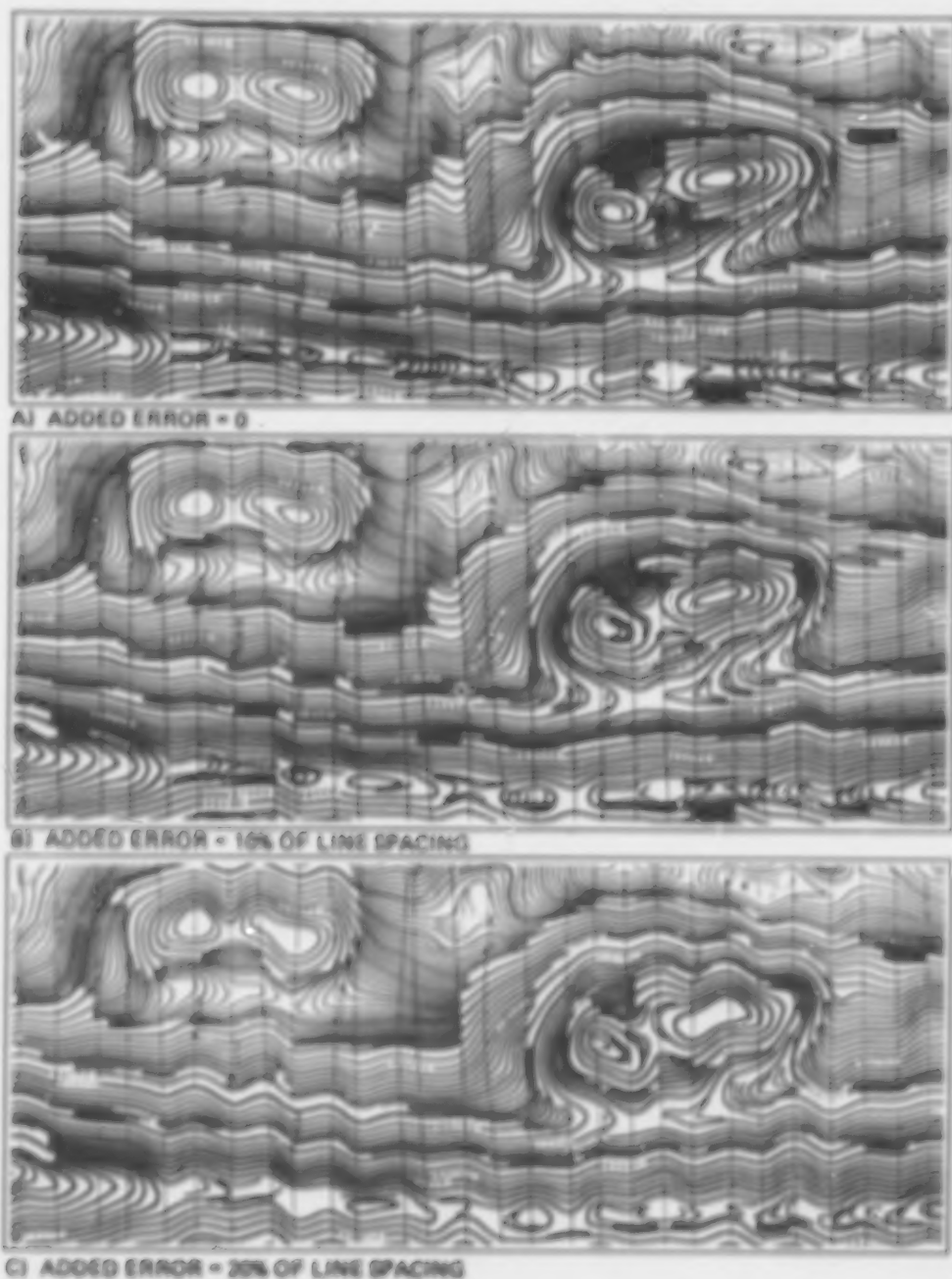


Figure 14.11. An illustration of the effect of positional error on a magnetic contour presentation. The data was collected at 50 m sensor elevation and 100 m line spacing. In the two lower maps, the data has been shifted in the flight direction by 10 and 20 m, respectively.

receiver was operated together with inertial and Loran C systems. With four satellites in view, the GPS system gave the needed accuracy. With only three or two satellites available, the inertial system provided the effective detail with drift corrections derived from satellite or Loran C data.

HIGH RESOLUTION SURVEY EXAMPLE

The first example is from the Hemlo area of Ontario, Canada, the site of a recent major gold discovery. Figure 16.12 presents the aeromagnetic data from three different aeromagnetic surveys with a 10 nT contour interval. Figure 16.12a presents data from the Geological Survey of Canada national coverage. The data was acquired at a mean terrain clearance of 300 m at a nominal line spacing of 600 m. Figure 16.12b presents the same area flown at a survey altitude of 100 m at a line spacing of 100 m. Figure 16.12c is again the same area but at an altitude of 50 m and line spacing of 100 m. The

contrast between the 300 m and 100 m survey altitudes is striking in terms of the added detail. The further reduction in survey altitude adds some further detail and an increase in amplitude of the small and narrow magnetic features is evident. A figure eight shaped anomaly is evident at the centre of the contour map (Figure 16.12c) that does not appear in the others. This survey was flown last, in 1984, and the anomaly is due to the mine site itself.

The second example is from the Casa Berardi area of Québec. Figure 16.13a presents aeromagnetic data collected at 150 m terrain clearance at a nominal line spacing of 400 m; the contours are at 20 nT intervals. Figure 16.13b presents an aeromagnetic map of the same area but at a terrain clearance of 50 m and a nominal line spacing of 100 m; the finest contours are at 2 nT intervals. The sequence is completed in Figure 16.13c with a presentation of the ground magnetic survey data collected at 120 m spaced lines and presented at 10 nT inter-

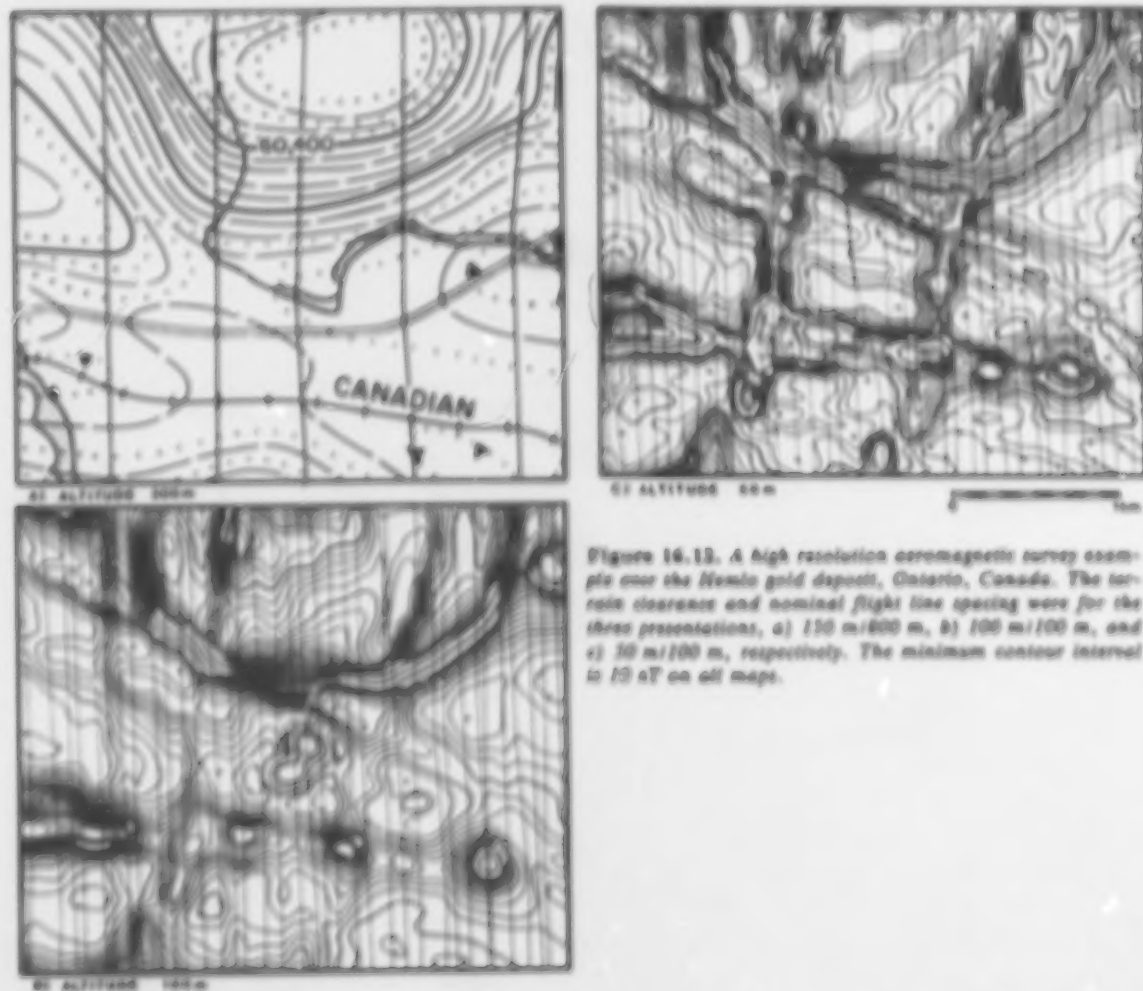


Figure 16.12. A high resolution aeromagnetic survey example over the Hemlo gold deposit, Ontario, Canada. The terrain clearance and nominal flight line spacing were for the three presentations, a) 150 m/600 m, b) 100 m/100 m, and c) 50 m/100 m, respectively. The minimum contour interval is 10 nT on all maps.

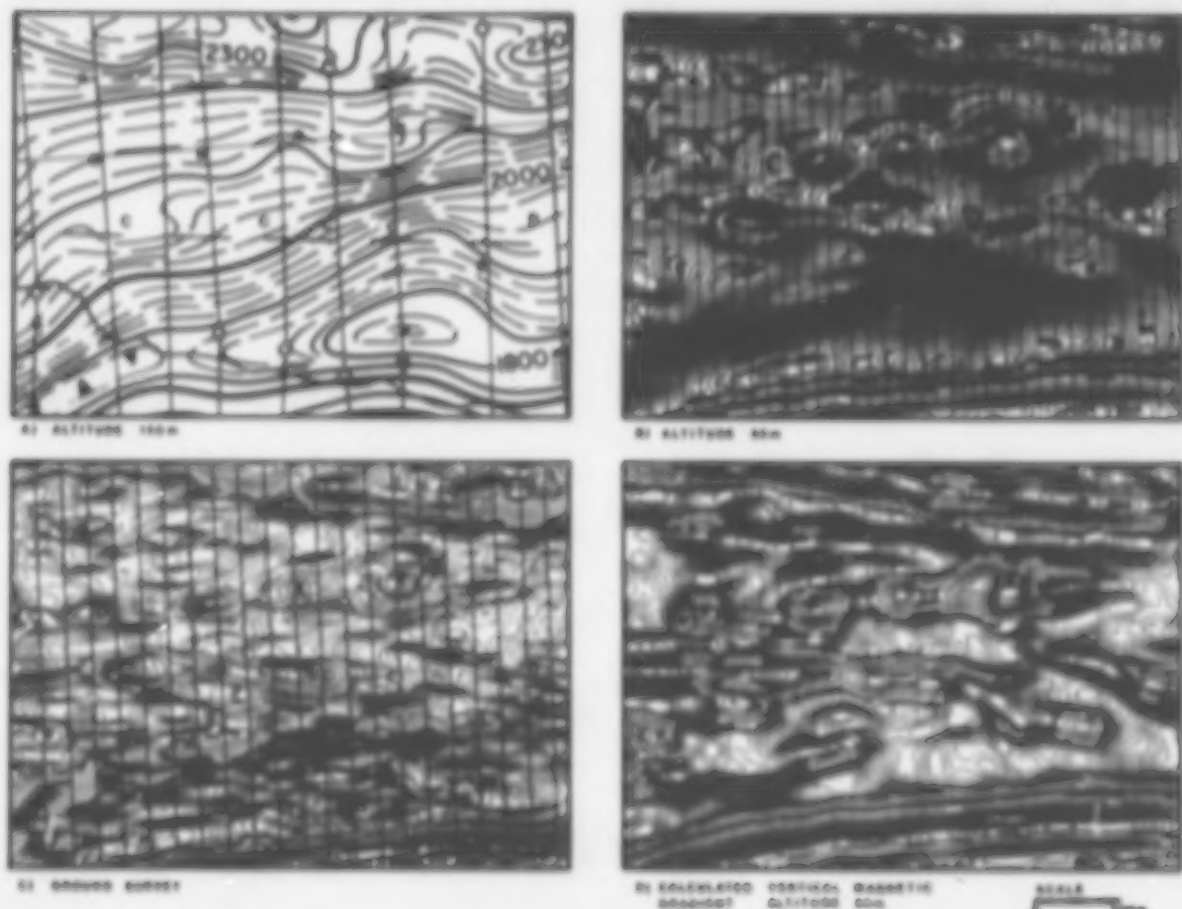


Figure 16.13. A high resolution aeromagnetic survey example from the Casa Berardi area of Québec, Canada. The terrain elevation and nominal line spacing were a) 130 m/600 m, b) 50 m/100 m and c) 0/120 a ground survey. The map d) presents the magnetic vertical gradients calculated from the total field data of map b). The letters A to G on the maps are provided for convenience of anomaly cross reference.

val contour. As in the previous example, a great improvement in detail is achieved with a three fold reduction in survey altitude.

An iron formation follows the top and bottom margins of the area introducing a magnetic gradient across the map. At 150 m altitude, the smaller magnetic features such as B and C, although roughly 60 nT in amplitude, show only as inflections within the gradient. The lower survey altitude of 50 m has increased the response amplitude of these anomalies relative to the gradient thereby improving their resolution. Nevertheless, anomalies E, F, and G, in the steeper gradient region are still apparent only as contour inflections. The vertical gradient presentation (Figure 16.13d) has been calculated to more clearly resolve anomalous activity close to the iron formation and the features thus identified are easily correlated with the detail of the ground magnetic survey.

CONCLUSIONS

The quality of aeromagnetic systems has improved during the past decade. Emphasis has been given to both high sensitivity as well as high sample rates, and gradient measurement systems are becoming relatively common. Both vertical and horizontal gradiometers provide valuable interpretive information and it is likely that the simultaneous measurement of both will be possible in the near future. High resolution surveys at altitudes in the order of 50 m and line spacings as close as 50 m are practical with modern navigation systems. Such detailed and positionally accurate data is becoming an integral part of detailed geological mapping for mineral exploration, and as a result the general application of aeromagnetics can be expected to grow in the coming decade.

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17. Real-Time Navigation and Flight Path Recovery of Aerial Geophysical Surveys: A Review

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ABSTRACT

The usefulness of aerial geophysical surveying depends upon the efficiency and accuracy of both real-time navigation and flight path recovery. Historically, a major advance was witnessed when Doppler radar systems were introduced to aid visual navigation and photographic recovery techniques. Early analog systems were replaced by microprocessor-controlled, digital-output Doppler, and high-resolution, colour positive video films superseded 35 mm photography, revolutionising the process of flight path recovery.

Over water and featureless land areas, the accuracy of Doppler techniques is reduced by the effects of water currents and the greater separation of reliable visual fixes. In these areas a variety of inertial or radio navigation systems have been employed. The choice of system is necessarily a compromise between range, accuracy, availability and economics, within the confines of the survey specifications.

The range limitations imposed by ground-based transmitters have been overcome by the recent application of GPS (Global Positioning System) satellites. Currently available "experimental" satellites provide only partial GPS coverage, but with careful selection and controlled use, they have been successfully employed on production surveys. With the proposed launching of further satellites and the introduction of improved receivers with rapid updates, GPS has the potential to provide a globally available, low cost navigation system to satisfy the requirements of most aerial geophysical surveys.

INTRODUCTION

This article reviews the accuracy, efficiency, and applicability of aerial navigation methods that have evolved since the first practical use of airborne geophysical surveys in the 1940s. Airborne geophysical surveying has traditionally been regarded as a relatively low-cost survey technique for both oil and mineral exploration so that the economics of using different navigation systems has been a major consideration in survey planning. The navigational aids in regular use today include:

- tracking camera (film or video)
- Doppler radar

- land-based radio navigation systems
- inertial navigation systems (INS)
- satellite positioning (GPS)

The dependence of these systems, apart from INS, upon electromagnetic radiation is illustrated in Table 17.1 (Sheriff 1984).

The objective of an integrated airborne navigation system is two-fold:

- It should help the pilot fly the required flight path.
- It must provide recoverable position fix information for post-survey plotting of the actual flight path within a required accuracy.

The responsibility of aircraft navigation and flight path recovery is rarely assigned to a professional surveyor. Typically, the pilot and co-pilot or navigator are responsible for flying the survey within specified tolerances; the electronics engineer is responsible for ensuring that electronic navigational aids are operational and synchronized or "time-tagged" to the geophysical measurements; the ground crew is responsible for recovering the flight path on to a map or mosaic and assessing the results. During the course of the survey, decisions are made as to whether the recovered flight path meets defined specifications with regard to line separation and terrain clearance or altitude. The actual positional accuracy of the flight path remains unknown, becoming apparent only when:

- ground crews attempt to locate specific anomalies
- data processing begins and the flight path undergoes either automatic or manual adjustment to produce satisfactory looking contour plots

Overall, there is usually very little information available on navigation accuracy. What has been well established is that surveys flown entirely on either Doppler or INS without reference to some form of visual control have produced some horrific errors of many kilometres in positioning.

The practical accuracy of flight path recovery is also dependent upon the scale of the available base maps, mosaics, or satellite images. If it is accepted that the minimum plotting error is 1 mm on paper, then the minimum plotting errors for different scale maps are shown in Table 17.2.

Satellite imagery is now being used frequently to create suitable base maps in remote parts of the

TABLE 19.1. ELECTROMAGNETIC SPECTRUM

Wavelength					Frequency
100 km	VLF		10-14 kHz	Omega	10 kHz
10 km	LF	LW	70-130 kHz 180 kHz	Decca Loran C, Pulse 8	100 kHz
1 km	MF	AM	1.6-3.0 MHz	Hyperfin Arpa Omnicast Turan	1 MHz
100 m	HF	SW			10 MHz
10 m	VHF	FM TV	140-400 MHz 200-450 MHz	Treant Satellite Triponder Mikoran Syndis GPS Satellite	100 MHz
1 m	UHF	TV	1.2-1.6 GHz		1 GHz
10 cm	SHF	MICRO- WAVES	3-10 GHz	Artemis Micradis	10 GHz
1 cm	EHF		8-13 GHz	Doppler Radar Radar Altimeter	100 GHz
1 mm					
10 ⁻⁴ m	INFRA- RED	THERMAL INFRA- RED			10 ¹² Hz
10 ⁻³ m					10 ¹³ Hz
10 ⁻² m		SHORT WAVE AND NEAR INFRA-RED	13 × 10 ⁻⁶ m	Land-based Thematic Mapper Airborne Thematic Mapper	10 ¹⁴ Hz
10 ⁻⁶ m	VISIBLE	VISIBLE			10 ¹⁵ Hz
10 ⁻⁷ m		ULTRA VIOLET	0.45 × 10 ⁻⁶ m		10 ¹⁶ Hz

TABLE 17.2 THE MINIMUM PLOTTING ERRORS FOR DIFFERENT SCALE MAPS.

Scale of Base Map	Flushing Error
1:25 000	25 m
1:50 000	50 m
1:100 000	100 m
1:250 000	250 m

world both for navigation and flight path recovery. Generally it has been found that Landsat MSS images can be successfully enlarged to 1:100 000 scale, Landsat TM to 1:50 000 and Spot (Panchromatic) to 1:25 000.

VISUAL TECHNIQUES

Pioneer geophysical surveys (Bohley 1932) relied solely on visual navigation where the pilot or navigator followed flight lines drawn directly on maps or, more usually, on either monals or air photographs. This technique is still successfully employed today

for some low level surveys. The flight path is recorded by a vertically mounted, downward-looking 15 mm camera, either as a continuous strip or as overlapping frames with sequential fiducial numbers controlled by an intervalometer or digital clock. Flight path recovery is achieved by the time consuming and labour-intensive process of examining, frame by frame, the black and white tracking film negatives to locate and plot identifiable features (Photo 17.1). The accuracy of the recovered flight path depends upon:

- the accuracy and scale of the base map, air photographs or photo mosaics. It is common to plot information initially onto a photograph and later transfer the plotted points onto a base map.
- the frequency of positively identified fixes. Without assistance from other navigational aids, the assumption has to be made that the aircraft has flown in a straight line at constant speed between plotted points.

Flies at 5 to 10 km intervals are considered sufficient for regional oil-type magnetic surveys, whilst 1 to 2 km is required for detailed mineral surveys.

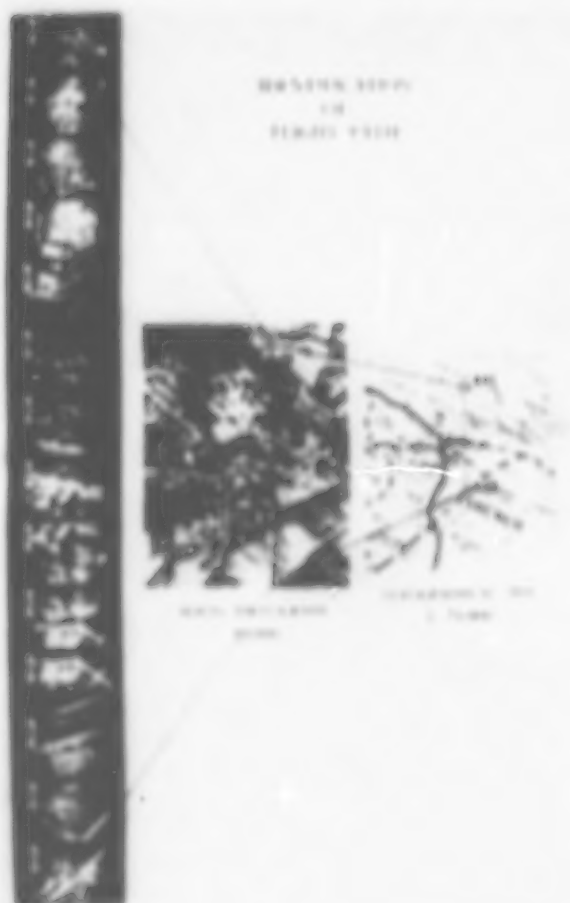


Photo 17.1 Flight path recovery using tracking film.

Often, the practical frequency of lines is determined primarily by the nature of the terrain and whether or not there are any recognisable features on the tracking film which may be related to the base map. It is now generally accepted that better accuracies are achieved by picking fewer but more certain lines and using an alternative navigational aid (e.g. Doppler or INS) to interpolate the flight path between lines.

One of the main advantages of tracking film is that flight path recovery may be achieved by matching overlapping flight line and control line images and picking intersection points (Figure 17.1). A whole survey grid may be recovered in this way and transferred onto a base map using a few additional lines. This technique, although time consuming, is particularly valuable in featureless areas or where base maps and aerial photographs are of poor quality.

The most serious tracking camera error is lack of synchronisation between the timing fiducials recorded on the film and those on the geophysical re-

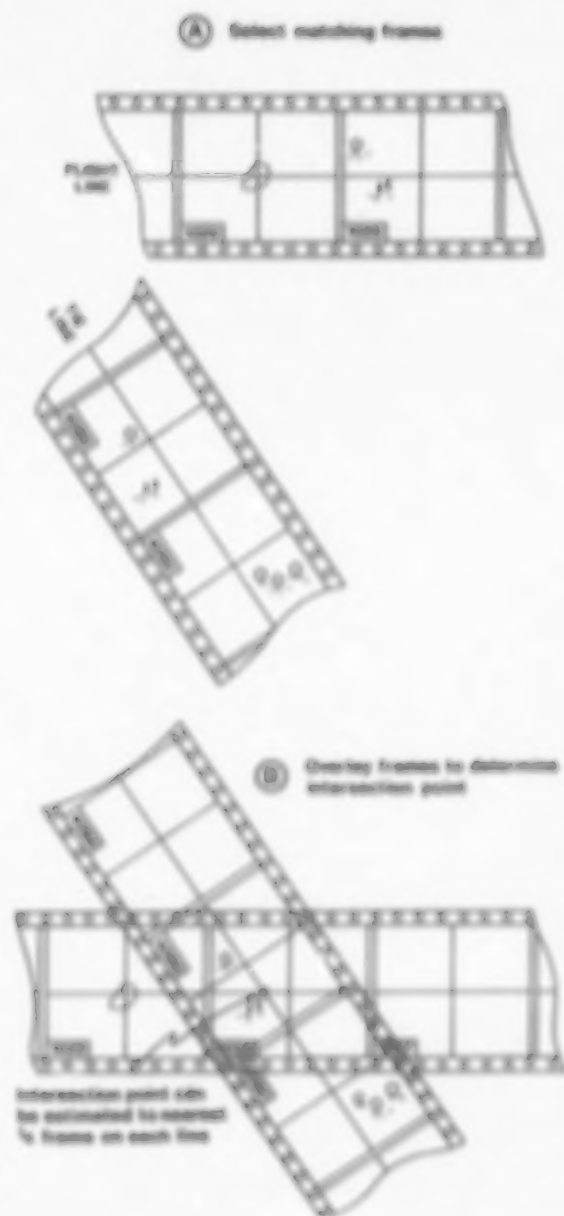


Figure 17.1 Location of flight line and control line intersections using overlapping 15 mm tracking film.

cords. This error produces herringbone effects seen on some contour maps but may be eliminated by triggering the tracking camera from the geophysical acquisition system. The position of tracking film fiducials, typically one second apart, in relation to the image may also be offset by an unknown amount producing errors of up to 100 m. In the case of aeromagnetic surveys, this constant offset may be corrected by measurements made in a "log test"; by

ing in opposite directions over an object producing a sharp magnetic anomaly. One of the main attractions of modern colour video cameras is that timing is more precise with a "freeze-frame" facility which can operate at 0.04 seconds; equivalent to an accuracy of approximately 2 to 5 m intervals.

Other errors associated with vertically mounted tracking cameras are more controllable. Aircraft roll or pitch of 30° would produce positional errors of 16 m at a terrain clearance of 100 m, but 160 m at 1000 m. This implies that for high altitude geophysical surveys a camera mounted in a damped gimbal system may be required.

DOPPLER NAVIGATION

Doppler radar is a self contained dead reckoning system capable of determining the aircraft's ground speed and distance flown both longitudinally and laterally. This is achieved by directing a radar beam of frequency 13.3 GHz towards the ground and measuring the change in frequency of the reflected signal (the Doppler effect). Usually three or four beams from the aircraft are directed forward, aft, and to either side of the plane, (Figure 17.2) giving both along and cross-track information. The recorded change in frequency (Δf) in the reflected signal is given by:

$$\Delta f = \frac{2Vf \cos A}{C}$$

where C = velocity of light

V = velocity of aircraft

f = Transmission frequency

A = Angle between V and direction of propagation.

If $V = 210$ km/hr, $A = 67^\circ$, $f = 13.3$ GHz, $C = 300\,000$ km/sec, then $\Delta f = 2.40$ kHz.

This represents a change of only 0.000180 percent in the transmitted signal. The practical way of measuring such small changes in frequency is by adding the reflected signal to a reference signal obtained from the transmitter and measuring the resultant beat frequency.

A Doppler system forms part of the avionics equipment in an aircraft and its installation requires modification to the airframe which is both time consuming and expensive. In the cockpit a display informs the pilot of aircraft ground speed and cross-track drift. The accuracy of a modern system is generally between 0.5 and 1 percent of the distance flown, but is dependent on several factors (Bacal-Ducos 1981):

- alignment of the zero position of the Doppler aerial with respect to axis of the aircraft
- accuracy of the Heading Reference system, i.e. compass

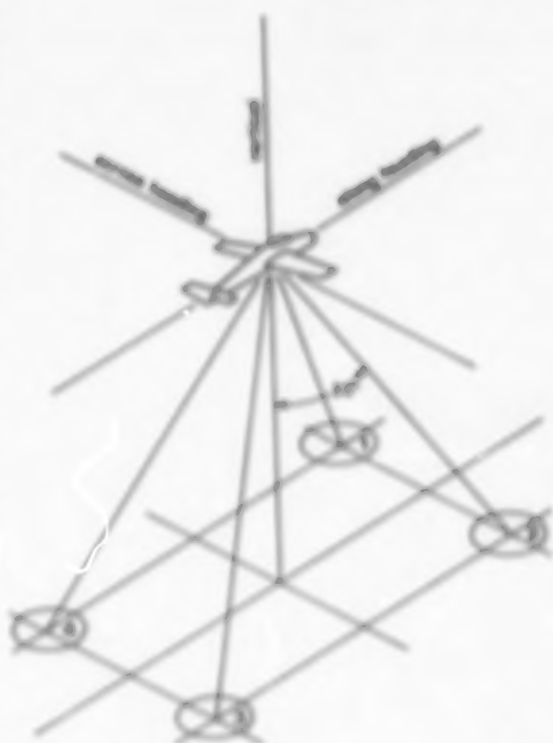


Figure 17.2 A 4-beam Doppler-Radar system.

- accuracy of the Attitude Reference system, i.e. vertical gyroscope
- compensation of compass heading for local/regional magnetic variation
- Low-level or contour flying over rough country, may affect the symmetry of the reflected signals, giving false ground speeds and drift. In severe cases the equipment may unlock.
- Poor reflections are encountered over still water and additional errors are produced by sea currents.

A major improvement in the efficiency and accuracy of flight path recovery techniques and indeed, airborne geophysical data compilation in general, was heralded by the introduction of fully synchronized digital Doppler and acquisition systems. Modern microprocessor-controlled Doppler systems now accept waypoint information, automatically compensate for aircraft motion, and output data in the form of UTM coordinates. At the field base, microcomputers are used to plot the data at the required scale with fiducial annotation. Doppler systems may be used to control the sampling rate of on-board geophysical instruments, so that digital recordings are taken at a constant distance interval rather than at constant time interval. This is particularly relevant in airborne spectrometer surveys and

permit sampling of usually 50 or 60 m lengths of flight line irrespective of changes in the aircraft's speed. Similarly, Doppler signals may also be used to drive analogue chart recorders to produce a specified accurate horizontal scale as well as driving the tracking camera, operating in a strip mode, to match the speed of the aircraft.

The main limitation of Doppler radar is that all systems drift with time, and therefore, like INS, require regular updating. Generally, Doppler is used by the pilot during survey flying as an aid for keeping on-line and during flight path recovery to interpolate the flight path between selected fixes, usually provided by a tracking camera.

RADIO NAVIGATION SYSTEMS

INTRODUCTION

Ground-based radio navigation aids may be conveniently divided up into five basic types:

- VLF 10 kHz systems, permanent chains e.g. Omega
- LF 100 kHz systems, permanent chains e.g. Loran-C, Pulse 6 and Decca
- MF 2 MHz systems, semi-permanent chains e.g. Hyperfix, Argos
- UHF 400 MHz semi-portable systems e.g. Epsilon
- Microwave 1 GHz portable systems e.g. Microfix, Acutape, Artemis

All of these systems comprise a number of ground-based transmitters and a mobile receiver (or transceiver) on board the aircraft. They operate in one of two basic modes known as hyperbolic mode or range-range (rho-rho) mode.

Hyperbolic Mode

In hyperbolic mode, a passive receiver on the aircraft measures either the difference in the arrival times or the phase differences between signals transmitted from two ground stations. These measurements are converted into the difference in distance between the receiver and the two transmitters. Lines of equal difference in distance, called lines of position, (LOPs), are hyperbolae which may be drawn on a navigation chart. The intersection of the two sets of hyperbolae obtained from two pairs of transmitters gives a positional fix (Figure 17.3).

Range-Range

In the range-range mode, the LOPs are circles obtained by measuring the distance directly from the receiver to two transmitting stations (Figure 17.4). Range-range measurements may be made in two ways:

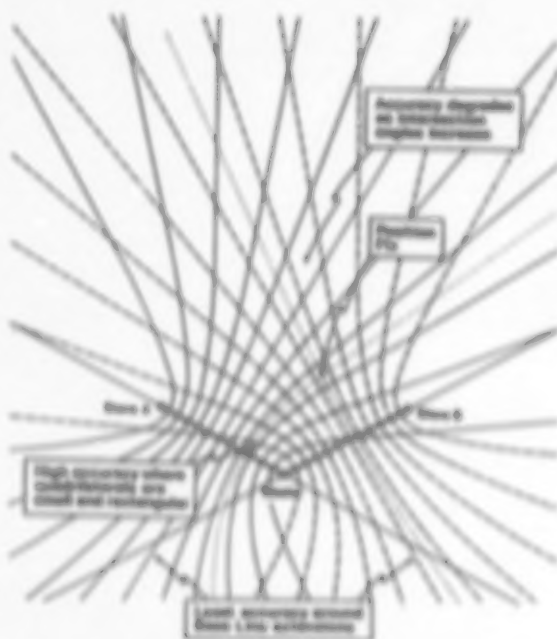


Figure 17.3 Hyperbolic radio positioning using one master and two slave transmitters arranged in a 120° baseline configuration.

- In an active mode, using a transmitter on the aircraft. Signals from the aircraft are sent to two ground slave stations capable of retransmitting (or reflecting) the received signal. The on-board receiver measures the return path transit times. The main disadvantage of active range-range measurements is that the number of mobile receivers capable of using the same transmitters is limited.
- In a passive mode, an atomic clock on board the aircraft knows the precise transmission times of the ground stations and permits the receiver to measure directly the time from receiver to transmitter.

A critical factor in determining the accuracy of range-range measurements is the intercept angle of the LOPs at the mobile receiver. Angles between 30° and 150° are generally acceptable (Figure 17.4) which implies that lines in the vicinity of the base line are unacceptable and that the distance between ground stations should be approximately half of the maximum operating range.

BASIC LIMITATIONS

In the selection of a radio navigation system there are several basic factors which should be considered (Sampson 1981; International Hydrographic Bureau 1981).



Figure 17.6 Range-Range positioning

GDOP (Geometric Dilution of Precision).

Each system has a specified range measurement accuracy. Unfortunately, positional accuracy is always worse than range accuracy since position is a function of at least two ranges. GDOP is a measure of the inaccuracies produced by different LOPs intersecting at different angles and is defined as:

$$\text{GDOP} = \frac{\text{standard deviation of positioning}}{\text{standard deviation of range}}$$

Generally GDOP is worse for hyperbolic than for range-range modes.

Multipath/Skywave

The propagation path of radio waves from transmitter to receiver is not constant and produces positioning errors. These are caused by skywave propagation at low frequencies (i.e. reflections from a chargeable ionosphere) and at high frequencies by multipath transmission (i.e. reflections off other objects) which leads to signal cancellation. Different systems are designed to minimize these problems in different ways.

Measurement Ambiguities

All systems making carrier frequency measurements have a measurement ambiguity which repeats itself every half-wavelength of the lowest modulating frequency. Similarly, time difference systems have measurement ambiguity problems and may require some confirmation of position by an alternative navigation device.

ASF (Additional Secondary phase Factor)

ASF (Strained et al. 1966) is an error term usually applied to Loran-C and Pulse E but which actually affects all systems. It relates to the reduced propagation velocities of signals transmitted over land and is caused by changes in surface conductivity. Permanent chains have the advantage that ASF errors may be partly established by calculating computed minus observed (C minus O) position for an area. Unfortunately ASF is not constant but changes with weather conditions and seasonally.

Frequency Allocation

For portable systems it is essential to verify that it is possible to obtain a licence to transmit on that frequency. Different countries have different regulations and several radio navigation bands are very overcrowded.

Calibration

Portable systems relying on time or time-distance measurements require precise calibration for transmission or receiver delays can be caused by changes in temperature and signal strength. The method and time taken to complete a calibration check varies for different systems.

VLF/LF SYSTEMS

The four main VLF/LF systems, Omega, Loran-C, Pulse E, and Decca are summarized in Table 17.3. All four systems require large permanent transmitters and have been developed for both air and marine navigational purposes. Only Pulse E, which is essentially a more accurate version of Loran-C, has been developed specifically for offshore survey work. All operate basically in hyperbolic mode although the two pulse systems, Loran-C and Pulse E do permit passive range-range measurements by using an accurate atomic clock in conjunction within the receiver.

Omega

Omega is a global hyperbolic radio navigational system, measuring the phase difference between continuous wave transmission in the 10 to 14 kHz range using eight transmitting stations situated in Norway, Hawaii, North Dakota, Argentina, Liberia, La Reunion Island, Australia, and Japan (Triley et al. 1984). Mobile receivers measure phase to better than 1/100 cycle or approximately 100 m, but the overall accuracy of the system is much less than this because of variable propagation conditions caused mainly by diurnal changes in the height of the ionosphere. More random propagation errors are produced by solar activity, thunder storms, and seasonal variations. Whilst some correction can be made for propagation conditions, the usual positional errors vary from 4 to 7 km. Differential Omega can improve positioning to better than 1 km by using a re-

TABLE 17.3. VLF/LF SYSTEMS.

System	Frequency	Measurement	Range (Propagation)	Accuracy	Transmitters (Power Output)	Remarks
OMEGA	10-14 kHz F ₁ 's	Hyperbolic C.W. Phase	Global (Skywave)	4-7 km Dif 1 km	Permanent All Tx's in open 3 stations world wide Spacing 4000- 10000 km (300 kW)	Distant segment connection. Propagation varies with season, solar activity, etc.
LORAN-C	100 kHz	Hyperbolic Pulse Timing	1000-1500 km (Groundwave)	30-100 m	Permanent. Many chains. Spacing 1000 km All Tx's in open (150-1500 kW)	Skywave effect removed by pulsing.
		Range-Range				With atomic clock timing
PULSAR-E	100 kHz	Hyperbolic Pulse Timing	500 km (Groundwave)	30-60 m	Permanent/ Semi Permanent Many chains Spacing 300-500 km All Tx's in open (10 kW)	Modern Loran-C Designed for survey work. Monitor stations to correct to distant areas.
		Range-Range				With atomic clock timing
DECCA Main Chain	70-130 kHz	Hyperbolic C.W. Phase	150-300 km (Groundwave)	30-100 m	Permanent Many chains Spacing 100 km (1.25 kW)	An old system Problems with skywave

tionary monitor receiver to record and broadcast corrections on a real time basis to mobile receivers within 100 km. Omega is seldom used as a primary navigation system for airborne geophysical surveys.

Decca Main Chain

Decca is a continuous wave-phase comparison hyperbolic system with transmitter stations spaced 100 to 200 km apart. A chain comprises a master and three slave transmitting stations which transmit only on common from the master. The chain works on a unique frequency f , (not transmitted) close to 14 kHz. The master and slaves transmit at frequencies which are fixed harmonics of f (master 8f, red slave 5f, green slave 5f, purple slave 5f). Phase comparisons between master and slave stations are made at frequencies of 24f, 18f and 30f for the red, green, and purple slaves respectively. These produce "beat line" lane widths of between 350 and 600 m. Lane identification signals are transmitted at regular intervals from all four stations which permit reconstruction of the fundamental frequency of 14 kHz with a lane width of 11 km (Tatley et al. 1984).

Decca has a useful operating range over water of 600 km by day and 400 km by night. The system is subject to errors caused by varying propagation conditions and has a positional accuracy of 30 to 200 m

dependent on distances to, and geometry of, the transmitting stations. Decca Main Chain is the oldest of the LF navigational systems with offshore chains being operational in Northern Europe, Eastern Canada, Japan, South Africa, and within localized areas in the Middle East and Australia.

Loran-C and Pulse E

Loran-C and Pulse E determine hyperbolic lines of position by measuring the difference in the arrival times of groups of pulses from pairs of synchronized transmitters. A transmitting chain comprises a master station and between two and five secondary stations, each of which transmits, in turn, a series of eight pulses at a specified group repetition interval (GRI)(Figure 17.5A). All transmissions, at a frequency of 100 kHz, are amplitude modulated to form a pulse of width 250 microseconds having a 63-microsecond rise time (Figure 17.5B). Course positioning is achieved using the arrival time of the whole pulse and higher accuracies by measuring the zero crossover time of the third cycle in the leading edge of the pulse envelope (Tatley et al. 1984). This technique prevents the groundwaves to be distinguished from the skywaves. Phase coding of pulses (i.e. making a pulse 180° out of phase with a normal pulse) allows receivers to distinguish between master and



Figure 17.6a. Loran-C Signal Pattern (After US Coast Guard, Department of Transportation, Loran-C User Handbook (10-682) - 1974.)

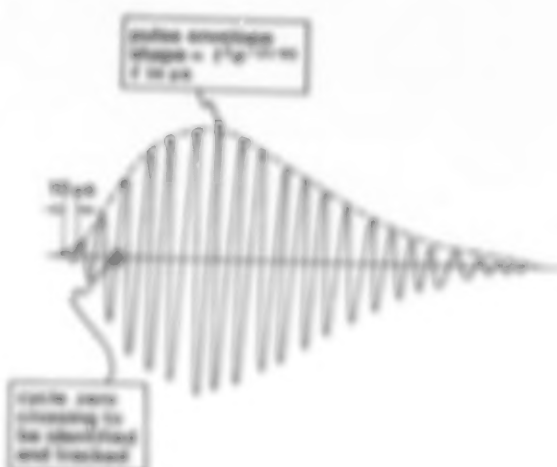


Figure 17.7b. Loran-C Pulse (After US Coast Guard, Department of Transportation, Loran-C User Handbook (10-682) - 1974.)

secondary transmission and is also of assistance in the presence of noise or weak signals.

Loran-C stations are widely spaced (1000 to 2000 km apart) and normally achieve positional accuracies of between 10 and 200 m. In 1985 there were 15 high powered Loran-C chains comprising 27 transmitters operating in the North Atlantic and Pacific Oceans. Coverage also exists in the Arabian Gulf and the Mediterranean.

Pulse 3 was developed specifically for offshore survey projects to give greater accuracy than Loran-C. An improved 20-40 m accuracy is achieved by using shorter base lines (500 km), by having improved geometry from more secondary stations, and by having more monitoring stations from which adjustments are made to transmissions to keep propagation times constant. Pulse 3 chains exist around the offshore United Kingdom and France, in the South China Sea and in the Java Sea. Modern Pulse 3 receivers are also able to record Loran-C transmissions.

PRECISE RADIO POSITIONING SYSTEMS

Table 17.4 summarises the large number of more precise radio positioning systems available today, operating in the MF, UHF and Microwave frequency ranges (Sampson 1991). The MF and UHF systems operate in both hyperbolic and range-range modes, while the microwave systems only operate in range-range. There is a trade-off between range, accuracy, and transmitter portability, all being functions of carrier wave frequencies. Modern systems are well adapted for airborne survey, having facilities for entering waypoints for the start and end of lines, the use of Kalman filtering and velocity feedback loops to correct for aircraft movement, and the display of real time navigational information to the pilot.

MF 2 MHz Systems

The 2MHz systems are generally used where ranges greater than 200 km are required. Most are continuous wave phase comparison systems, using the ground wave, with a practical positioning accuracy from 2 to 25 m. The main disadvantage of 2 MHz systems are skywave problems and varying propagation velocities over land and sea. The Geosol and Spot Systems use broad band pulsed-radiosonde transmitters in an attempt to discriminate groundwave from skywave signals. Both of these systems also permit passive range-range measurements to be made using an accurate constant clock.

UHF 400 MHz Systems

The 400 MHz systems can achieve ranges of up to 400 km from the base transmitters. UHF signals are conventionally transmitted beyond the line of sight (LOS) in a "surface duct" which forms between the water or land and a refractive temperature inversion in the atmosphere. Accuracies at two to three times LOS distances are difficult to predict but are generally in the range of 11.5 m. Transmitters are portable, or semi-portable when power boosters are used to achieve greater range. All systems use pulse timing and operate conventionally in either hyperbolic or active range-range modes.

Microwave Systems

The microwave systems have truly portable transmitters with positive high accuracy (1 to 3 m). They are limited to LOS ranges so that the actual height of the transmitter stations determines the range possible. Microwave systems operate in the active range-range mode and use two distinctly different principles to measure distance; the time of arrival of a pulse envelope and the phase delay of modulation waves. Phase measurements have a higher accuracy but pulse measurements have a greater flexibility. The main disadvantage of microwave systems is that multipath transmissions frequently distort the primary signal by reflections from mountains, buildings, vehicles, antennas, etc. Correct transmitter locations

TABLE 17.4. PRECISE POSITIONING SYSTEMS.

Frequency	Systems	Measure- ment	Range (Propagation)	Accuracy	Portability (Power Output)	Remarks
MF 2 MHz (1.0-3.4 MHz)	ARGO GEOLOC HYDROTRAC HYPERFIX RAYDIST SPOT TORAN	Hyperbolic C.W. Phase Some spread spectrum systems. Also active Range-Range.	200-500 km Greater during daylight hours (Groundwave)	5-25 m	Large permanent antennas. (100-300w)	Skywave problems at night. Lane count errors. Propagation velocity errors. Best choice when distances >150 km.
UHF 400 MHz (200-450 MHz)	MAXIRAN SYLEDIS TRIDENT TRISPONDER SHORAN	Hyperbolic Range/Range Pulse	200-400 km (surface "ducts")	2-10 m	Systems semi- portable. Large antennas required for longer ranges (100-1000w)	Errors increase when distance is 2 to 3 times LOS Suitable for airborne survey.
Microwave (3-10 GHz)	ARTEMIS AUTOTAPE CR-100 MAPS TELLUROMETER MICRO-FIX MINIRANGER TRISPONDER	Range-Range Pulse envelope Phase modulation.	50-200 km (LOS) (Depends of Tx height.)	1-3 m	Very portable (1-100w)	Suitable for airborne survey. Errors caused by multipath reflections. Pulse more flexible. Phase more accurate.

and the use of restrictive beam widths are the techniques used to resolve these problems.

INERTIAL NAVIGATION SYSTEMS

Inertial navigation systems (INS), like Doppler systems, are dead reckoning, self-contained units, operating independently of remote stations. A traditional INS system comprises a gyro-stabilized platform onto which are mounted three mutually perpendicular accelerometers. The principle of operation is the application of Newton's first and second laws of motion with linear motion being detected by the accelerometers and the rotational motion by the gyros. The gimbal mounted platform is maintained in a fixed angular orientation in space by coupling the gyros to servomotors. Component velocities and changes in distance of the aircraft (D_x , D_y , D_z) are determined by single and double integration of the output of each accelerometer with respect to time. It is essential that the platform is maintained horizontal at all times and not merely occupying a fixed position in space. This necessitates that control signals are fed to the gyros to correct for both rotation of the earth with time and the velocity of the system round the circumference of the earth. This correction, known as Schuler loop tuning is illustrated in Figure 17.6 (Smith 1986) and includes corrections for Coriolis forces acting on the accelerometers.

Another source of error is the effect of gravity acting on the horizontal accelerometers when the platform is not exactly horizontal. As the system

cannot distinguish between true accelerations and the acceleration due to gravity, this produces an oscillatory error which is a feature of all inertial systems and has a period T , known as the Schuler period of:

$$T = 2\pi \left(\frac{R}{g} \right)^{\frac{1}{2}} = 84.4 \text{ minutes}$$

where R is the radius of the earth and g the acceleration due to gravity.

INS equipment is regularly used in helicopter borne gravity surveys where the system is capable of determining x, y, z positions to better than 1 m, with post survey processing. For successful survey operations it is necessary to start from a known point, to land every five minutes so that the INS can update

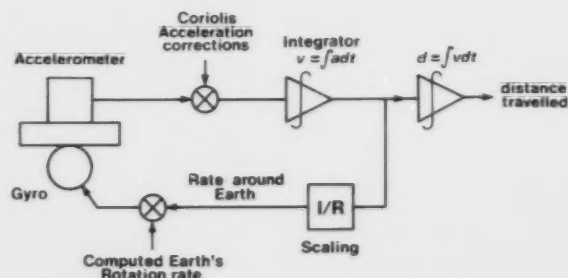


Figure 17.6 INS system illustrating Schuler loop tuning.

itself when stationary, and to return to a known position every three hours.

For a continuous airborne geophysical survey, INS equipment has acquired a role analogous to Doppler radar as an auxiliary backup navigational aid. It has been used with considerable success in conjunction with tracking camera and radio positioning systems both onshore and offshore. As INS suffers from drift and sinusoidal variations (84 minute period) the system requires regular updates every 15 or 20 minutes. This is usually achieved by flying over a known geographical position or by using radio positioning fixes. Post processing of INS data, correcting for drift and Schuler effect can produce accuracies to within 100 m.

Modern developments in INS technology have produced so-called "Strapped Down" systems where computers replace the stabilized platform. Mechanical gyros are also being replaced by ring laser gyros (RLG) which contain no moving parts. RLGs detect rotational motion by the Doppler effect operating on two laser beams which travel in opposite directions around a glass triangle and are combined to produce interference fringes. To date there is no record that these developments have been incorporated into INS systems used for airborne geophysical surveys.

SATELLITE NAVIGATION SYSTEMS

There are two main satellite navigation systems known as Transit Doppler and Navstar Global Positioning Systems (GPS) which are operated by the United States Navy and Department of Defense respectively. The seven Transit satellites are in circular polar orbits (107 minute period) at an altitude of 1 100 km. Transit receivers measure the Doppler shift in the transmitted satellite signals (400 MHz, 150 MHz) from which the position of the receiver may be calculated. As Transit takes 15 to 20 minutes to obtain a basic positional fix from a single satellite, the system has no direct application to air survey navigation apart from being an ideal system for accurately positioning radio navigation transmitting stations on the ground.

GLOBAL POSITIONING SYSTEM (GPS)

GPS is perhaps the most exciting development that has ever occurred for land survey and navigation. To date (1987) the system is partly operational with only seven prototype Block I satellites in orbit. Delays in satellite launches have been caused by problems with the NASA Space Shuttle program but it is still predicted that by the early 1990s GPS will be fully operational (Sherrer 1986).

The complete system will comprise 24 Block II satellites arranged in 6 orbital planes at an inclination of 55° to the equator. Orbits will be nearly circular at an altitude of 20 200 km and having a period of 12 hours.

The three components of GPS, the ground control system, the satellites and the receiver are illustrated in Figure 17.7. GPS satellites transmit continuous synchronized signals on two L-Band (UHF) frequencies, 1.575 GHz (L1), 1.227 GHz (L2). The signals are modulated with a "Precise" P-code, and a "Coarse Acquisition" C/A-code and contain a navigational message. The C/A code, which repeats itself every millisecond, is intended for commercial users. The more accurate P-code is intended for military use only. The navigational messages include details of errors in the satellite's clock, ionospheric propagation correction parameters, details of the satellite ephemeris and almanac together with broadcasts of satellite time (Wells 1986).

There are two basic types of GPS receiver, geodetic receivers which have to remain stationary, and navigation receivers which track the movement of the vehicle in which they are installed. Recently some receivers have been built which fulfil both of these functions.

A GPS receiver acquires the satellite signal and measures the range, or more correctly the pseudo-range, to the satellite by multiplying signal propagation time by the speed of light. The term pseudo-range is used because the time difference between the receiver's clock and the satellite's clock is not known (Blanchard 1986). By pseudo-ranging to 4 satellites simultaneously (4 equations, 4 unknowns) it is possible to determine the receiver's 3-D position and the receiver's clock errors. Typical accuracies using the C/A code in a dynamic mode are 20 to

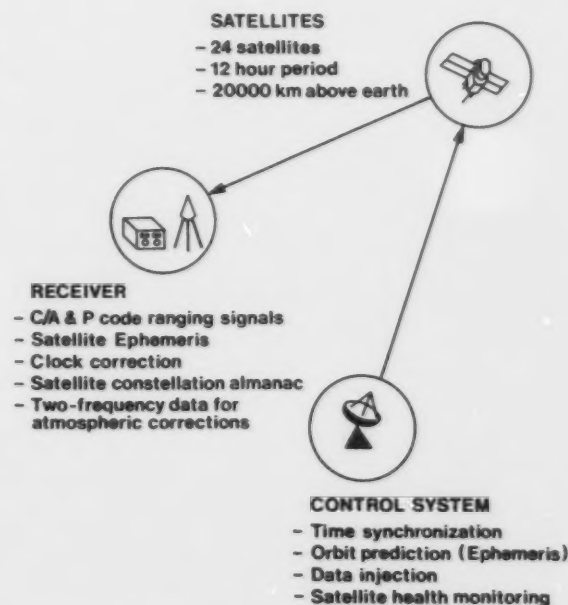


Figure 17.7 Components of GPS (After Wells 1986).

30 m in latitude, longitude and elevation (x,y,z) (Napier *et al.* 1987).

Considerable improvements in accuracy may be achieved by differential GPS (DGPS) techniques in which one receiver remains permanently fixed at a known location and tracks the same satellites at the same time as the mobile receiver. The stationary receiver provides error corrections (e.g. clock, orbit, propagation) either in real time, through a communications link, or for post data processing. Dynamic accuracies of 3 to 5 m are obtainable using DGPS techniques.

The predicted lifespan of a Block I satellite is only 5 years, so planning is already underway for the design of Block III satellites ready for launching after 1995.

NAVIGATION CASE HISTORIES

VISUAL TECHNIQUES

In 1987 a helicopter borne radiometric survey, flown by Global Earth Sciences in a mountainous region of Greenland, employed visual navigation and a video tracking camera (Global Earth Sciences 1987). The survey was flown along a series of contour flight lines at 30 m intervals of elevation. An inclined radio altimeter beam was used to maintain a constant distance of 30 m from the side of the mountain. Regular calibration of the barometric altimeter was made at control points. The video film was used to recover the flight path on to 1:5000 scale controlled photo mosaics. A sampling crew of mountaineers and geologists equipped with scintillometers undertook immediate ground follow-up of selected uranium anomalies and established a positional accuracy for the flight path of between 10 and 30 m.

DOPPLER, OMEGA, AND CONVENTIONAL RADAR

The British Antarctic Survey (BAS) flew aeromagnetic and ice thickness radar (60 MHz) survey of the Ronne Ice Shelf, Antarctica, during the 1982–83 and 1983–84 field seasons (Herrod *et al.* 1986). Omega proved unreliable due to absorption of VLF signals by the ice sheet. A Decca Doppler radar unit was used as the primary navigational aid, which gave excellent reflection from the ice shelf and an RCA Primus colour radar was used to locate fuel dumps. The fuel dumps, which had previously been accurately positioned by a Transit satellite receiver, provided control to correct the Doppler navigation for along-track and across-track drift. At high magnetic latitudes the magnetic compass heading reference for the Doppler had to be updated manually for changes in magnetic declination (every 0.3°) in order to maintain an accurate heading. This resulted in the Doppler output generally being accurate to better than 1 percent of the distance flown.

RADIO NAVIGATION AND INS

In 1982, Hunting Geology and Geophysics conducted an aeromagnetic survey over a 50 000 km², predominantly offshore area, encompassing a group of tropical islands. Syledis, as the primary navigation system, was operated in hyperbolic mode with a chain of four unboosted beacons (located on islands) giving an effective range of 200 to 250 km. The INS was operated simultaneously with Syledis, using both visual updates and geographical coordinates by the Syledis system to correct for drift and Schuler oscillations. Doppler was used as a navigational aid to the pilot.

The flight path was recovered in the field from Syledis printouts (and later in the laboratory from the digital cassettes) and compared with the tracking camera over the land areas. No significant errors were recorded. By comparing the raw INS data (i.e. not updated) with both Syledis and visual navigation, an INS correction equation was solved which included terms for linear drift, Schuler oscillations and an empirically derived parabolic term. This permitted INS navigation to be used on lines beyond the range of the radio chain and also provided infill data during periods of poor Syledis reception (Figure 17.8).

GPS AND PULSE 8/LORAN-C

In 1985, Hunting Geology and Geophysics conducted a 50 000 line kilometre magnetometer survey off the coast of central Norway utilizing a Trimble 4000A GPS receiver as the primary navigation aid with Pulse 8/Loran-C as the secondary system (Jones 1987; Hunting Geology and Geophysics 1985). A tracking camera provided a dynamic check on the accuracy of each system by flying over a lighthouse at the beginning and end of each sortie, and a Doppler radar provided additional steerage to the pilot. The survey was flown at a constant altitude of 240 m (maintained using both barometric and radar altimeters). This height was entered into the GPS receiver as the value for elevation (z-value) enabling the survey to be flown by tracking only three satellites to obtain latitude and longitude (x,y). Each day there were two approximately four-hour periods when three satellites were in view and it was found that survey flights could be extended by approximately one hour by tracking only two satellites in conjunction with an on-board atomic clock.

Positional errors whilst tracking three satellites were 50 m or better but from two satellites errors of up to 300 m were recorded which were believed to be produced by a linear drift in the atomic clock from commencement of two-satellite tracking.

Approximately 90 percent of the survey navigation was recovered using GPS data whilst Pulse 8/Loran-C were used for the remainder. Comparisons between GPS and Pulse 8/Loran-C were made throughout the survey and correction charts com-

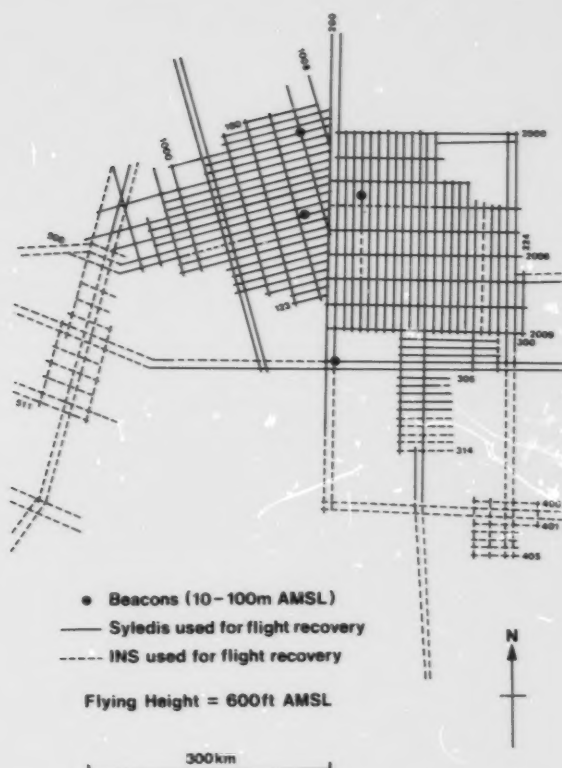


Figure 17.8 The recovered flight path for an aeromagnetic survey using a combination of Syledis and INS navigation.

piled, (GPS computed minus Pulse 8/Loran-C observed) which enabled Pulse 8/Loran-C to be corrected to within 50 m of the GPS position. These charts were used whenever GPS data were either non-existent or of unacceptable quality.

THE FUTURE OF AIRBORNE SURVEY NAVIGATION SYSTEMS

The potential of GPS as a revolutionary navigational aid for airborne geophysical surveys has been demonstrated by the seven prototype Navstar satellites in orbit today. A fully operational GPS system requires no special charts, is capable of operating anywhere in the world at any time and with no additional costs once a receiver is purchased. GPS satellites orbit at an altitude of 20 200 km and are therefore less affected than the lower Transit satellite orbits by localized changes in the earth's gravitational field. GPS is expected to open up new techniques for both airborne geophysics and aerial photography. It should be possible to eliminate the premarking of ground points for photogrammetric control by placing GPS sensors on aircraft wingtips and tail so that the exact position and attitude of the plane is known at all times during a photography survey (Wells 1986).

Similarly GPS sensors could be placed on magnetometer sensors (birds and stingers) so enabling wide spaced magnetic gradiometry measurements to be made. Perhaps the most significant effect will be felt in airborne gravity where DGPS will permit aircraft heights to be determined to an accuracy of 1-2 m and aircraft velocities to better than 10 cm/sec.

The accuracy of any positional fix is dependent upon two factors; the range measurement accuracy, and the effects of satellite geometry which is expressed by the Dilution of Precision (DOP) factor. The recent announcement that there are now going to be 24 operational GPS satellites instead of the originally planned 18 greatly improves the PDOP (Positional Dilution of Precision) for the system. PDOP is a function of the relative position of satellites which varies with time and necessitates changing constellations in order to maintain acceptable accuracies for fixes (Blanchard 1986). It is also probable that the three Inmarsat telecommunication satellites in geostationary orbit over the Atlantic, Indian and Pacific oceans should be used as pseudo GPS satellites (C. Beatty, Magnavox Survey System Incorporated, personal communication). This would be particularly valuable in checking the integrity or health of the other satellites and relaying the information to GPS receivers.

It is planned that sometime in the future the C/A code will be degraded by the United States Department of Defence to produce instantaneous positional accuracies of only 100 to 250 m. This may have been brought about by better than expected accuracies achieved with the prototype GPS system. One possible reason for this improved accuracy is the ideal radio propagation conditions experienced in a period of quiet sunspot activity (1986-87). It is possible that natural degradation of the C/A code may occur as solar activity increases. Whether or not the C/A code is degraded may have ultimately little effect on navigational accuracies as the use of improved DGPS techniques are expected to more than overcome any reduction in accuracy.

The use of pseudolites are likely to have very significant effects on future airborne survey techniques provided that their cost is not prohibitive. A pseudolite is, in effect, a "GPS satellite" which is placed in a known position on the ground and transmits a signal in the same format as a GPS satellite. Pseudolites will both improve the geometry of the fix and make use of the GPS receiver for a DGPS data link. The first prototype pseudolites have only recently been built.

One of the few problems with GPS is that it is difficult to maintain continuous reception from all three or four satellites which are being tracked simultaneously. This effect has already been noticed in the air when the aircraft is turning, and on the ground when signals are blocked by trees, buildings, or vehicles. If this effect proves to be a serious problem then INS, Doppler and the tracking camera may

survive in the future as backup navigational aids which work in conjunction with GPS for updates and infills. With regard to the existing radio positioning systems, it is anticipated that provided that GPS production satellites are launched as planned then Decca will only survive to the early 1990s, Loran-C and Pulse 8 to the mid 1990s, and Omega possibly to the 21st Century for submarine use. Of the more precise higher frequency systems, (2 MHz, 400 MHz, and Microwave) these will only survive until GPS becomes the more economic and efficient system to use with comparable accuracy.

For airborne geophysical surveys, GPS will provide instantaneously a reliable flight path in digital form which offers the potential for undertaking data processing in the field. Whilst video cameras are still likely to be used as the only navigational aid available which relates directly to features on the ground, it is possible that their role will be secondary for checking on the accuracy of the GPS flight path. It is expected that small portable GPS receivers will eventually be more accurate and much easier to use than aerial photographs for the ground follow up of selected anomalies.

Predictions have been made that by 1995, GPS receivers will cost as little as US\$500 and be the size of a cigarette packet. We may then all have one to tell us where we are at all times, just in case we really need to know!

ACKNOWLEDGMENTS

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18. Advances in IP Technology: Telluric Cancellation and High Spatial Resolution Arrays

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ABSTRACT

Two aspects of IP technology are examined: real-time telluric noise cancellation and high spatial resolution arrays. Exploration for deep IP targets, particularly in conductive environments, can encounter severe data degradation due to telluric noise. Telluric cancellation can provide valid IP data, even broadband IP data at long pulse lengths, where uncanceled data are unusable. Remote or hard-wired telluric configurations can be used. A telluric cancellation bipole has been used successfully with the pole-dipole array. Methodology for real time telluric cancellation is discussed. Minerals exploration case studies are presented for which telluric noise was reduced 1 to 2 decades.

Spatial resolution can be increased by modeling and interpretation of combined pole-dipole and dipole-pole data sets representing a large number of potential dipoles. Arrays that acquire such data sets are herein labeled high spatial resolution arrays. At the Pinson gold mine, such arrays mapped the major geologic features, including zones of calc-silicate alteration in the gold ore host rock. A survey at the Quartz Mountain gold deposit detected and indicated the direction of dip of two flat-dipping gold-bearing units. Broadband IP distinguished micro-fine pyrite in one unit from coarse, veinlet sulphides in the other.

INTRODUCTION

This paper will examine two aspects of IP technology: telluric noise cancellation and high spatial resolution arrays. A common theme is methods and technology for the acquisition and use of data that are of high quality, both in the temporal signal-to-noise sense and the source-resolution sense. Following an opening discussion about arrays, the paper will examine the cancellation of telluric noise from IP data, particularly for deep IP targets in conductive environments, where signal-to-noise problems can be severe. Telluric noise cancellation methodology is reviewed and case studies from minerals exploration are presented. Following the discussion of telluric cancellation, the paper will consider the topic of detailed IP measurements using high spatial

resolution arrays. Specifically, it will examine the use of such arrays, coupled with forward modeling, as a detailed geological mapping tool in gold exploration.

COMPARISON OF IP ARRAYS

The choice of array for an IP survey depends on various factors: personal preference, logistics, equipment, operating and interpretation software, safety, environment, and others. A full comparison is beyond the scope of this paper, but some comments will be made related to deep IP targets and telluric cancellation. This paper touches on another aspect concerning arrays — inherent information content — so some comments will be made regarding that, also.

As regards two in-line arrays, dipole-dipole and pole-dipole, there are many trade-offs. Many prefer to interpret dipole-dipole data because of the symmetric shape of the anomalies on a pseudo section. Dipole-dipole requires less current wire to be laid out. The EM coupling using dipole-dipole is averagely comparable to that using pole-dipole with an orthogonal infinite current, but it is generally better behaved, since the current dipole length is always constant. On the other hand, pole-dipole yields much better signal-to-noise than does dipole-dipole at larger values of η (at $\eta=6$ the signal-to-noise is 4.0 times larger with pole-dipole), so that it is inherently better for applications where signal-to-noise is a problem. Also, given automated, multi-channel systems, pole-dipole is very amenable to the use of a large number of potential dipoles for very detailed measurements. Pole-dipole and dipole-pole (same array as pole-dipole except the potential dipoles are on the opposite side of the current electrode) may be measured simultaneously.

Concerning the detail aspect, the maximum η value that might be used for a dipole-dipole survey would in general appear to be quite limited, since the signal decreases as $1/\alpha\eta^3$ (α =dipole length), versus $1/\alpha\eta^2$ for pole-dipole and $1/\alpha\eta$ for pole-pole. However, this limitation may not be critical, since there are probably not compelling reasons to use dipole-dipole in the strict sense that the dipole length is held fixed at a single value of α .

Using automated, computer controlled IP systems, data could be collected in one configuration

and presented in another. For example, data collected pole-dipole could be presented in that mode (for good signal-to-noise, say) or in dipole-dipole mode (for a preference of anomaly symmetry, say), to exploit the advantages of each. Converting pole-dipole data to dipole-dipole would require the data to be of high quality, since the converted data will be of generally similar signal-to-noise as if acquired in the dipole-dipole mode. To boost the signal-to-noise of the converted data, the voltages could be combined to yield alternative dipole-dipole pseudo sections with greater dipole length and a lower range of η values.

In theory, there is a descending order of inherent information content from pole-pole, through pole-dipole, to dipole-dipole. Looked at as approximations to derivatives (finite differences), pole-pole measures the potential due to a point source, pole-dipole measures the first difference of the potential, and dipole-dipole measures something akin to a second difference (due to creation of current dipole from current poles by voltage subtraction). High quality pole-pole data can be transformed to the pole-dipole (or dipole-pole) array, which in turn can be transformed to the dipole-dipole array. But, because of a constant-of-integration type requirement, the process cannot be reversed. Dipole-dipole data cannot be transformed to pole-dipole, and pole-dipole data cannot be transformed to pole-pole. In addition, dipole-pole data cannot be transformed to pole-dipole data, and vice versa, which suggests that there may be interpretational advantages in running both.

The conditions under which the additional information provided by pole-dipole or dipole-pole, as opposed to dipole-dipole, significantly aids an interpretation is generally not well defined. However, as one instance, it appears that dipole-dipole tends to attenuate the IP response of very large, deep sources, as compared with pole-dipole (quite apart from temporal signal-to-noise considerations). The conditions under which the combined use of pole-dipole and dipole-pole data significantly aid an interpretation are also not well defined. However, in this paper the authors present case studies wherein pole-dipole and dipole-pole arrays used in combination gave a more definitive, less ambiguous interpretation (based on modeling) than either array used alone.

TELLURIC NOISE CANCELLATION

Exploration for deep IP targets, particularly in conductive environments, can present severe temporal signal-to-noise problems. These problems usually relate to EM coupling, telluric noise (Sumner 1976), and weak signal voltages. For measurements over conductive ground using large separations between current and potential electrodes, the EM coupling voltage decays very slowly. Since large separations

are required to probe for deep targets, transmitters must be operated at long pulse lengths and measurements must be made at long decay times, sometimes several seconds, in order for the EM coupling component to attenuate. At long pulse lengths, telluric noise can be extremely severe, even after maximum practical cycle stacking. However, telluric cancellation can greatly improve signal-to-noise, allowing measurement of valid IP — even spectral IP — in such environments. Telluric cancellation can also be useful for measurement of high quality broadband IP data in less demanding environments.

Real time telluric cancellation had its roots in bridge-based noise cancellation methods developed at Anaconda Minerals by E.O. McAlister, M.O. Halverson and others during the 1960s to acquire high quality broadband IP data in the time-domain. These methods, for spot soundings and in-line-array measurements, used an IP receiver with chart recorders and a two-component bridge to balance-out the telluric noise. In a 1967 survey near Yerington, Nevada, noise rejection of about 50:1 was often achieved using a spot sounding configuration and measuring deep-looking IP to 5 minutes pulse length. The technique worked well in other areas too, but in still other areas it provided little noise rejection.

Telluric noise cancellation using multi-channel digital systems followed a few years later, and a production multichannel IP system with real time telluric noise cancellation was put in the field in 1979 for minerals exploration. That system and a replacement model developed by Atlantic Richfield Company were also extensively used for petroleum research and exploration.

TELLURIC CANCELLATION METHOD

The basis of telluric noise cancellation of IP data is that (Berdichevskiy 1965) the telluric voltage, V_{TU} , on a random, u-oriented dipole can be synthesized by a linear combination of telluric voltages V_{TX} , and V_{TY} , on orthogonal x- and y-oriented dipoles located several or more kilometres away. The relationship is expressed by the following approximation:

$$V_{TU} - (AV_{TX} + BV_{TY}) = 0 \quad (1)$$

Where A and B determine the linear combination, and will be referred to as the telluric coefficients.

For real-time telluric noise cancellation, the telluric reference voltages, V_{TX} and V_{TY} , might be measured on orthogonal dipoles located a long distance from an IP line and transmitted to the IP receiver by digital radio telemetry, as in an existing Atlantic Richfield system. Such telluric cancellation has been used for IP surveys with the pole-dipole array. In using this form of telluric telemetry with pole-dipole, EM coupling must be carefully considered. Significant EM coupling voltage can persist on the telluric dipoles out to very long decay times; due

both to the large separation between remote site and IP line, and the great length of the current dipole. Remote site telluric measurement is well suited to dipole-dipole, since both the IP decay voltage and — more critically — the EM coupling voltage fall off rapidly with distance, due to the short length of the current dipole.

There are alternative, hard-wired versions of telluric cancellation as well. For deep-looking exploration using the pole-dipole configuration with orthogonal infinite current, a long in-line telluric cancellation bipole (Halverson 1982) can be used either with or without an orthogonal telluric dipole. Case studies are presented in this paper. This bipole technique is not suitable for dipole-dipole, since the IP voltage across the bipole tends to be too large. For dipole-dipole surveys, an inline telluric dipole placed at an η of eighteen or more from the current dipole might be acceptable. The orthogonal dipole, if used, could be placed much closer to the current dipole, since the electrodes would tend to be on an equipotential.

The in-line telluric cancellation bipole technique, developed at Atlantic Richfield Company (Figure 18.1), uses a roving current (C), a string of potential dipoles, and a telluric bipole. The return current is at infinity, roughly orthogonal to line to minimize EM coupling. The string of potential dipoles may either trail or lead the current. Alternatively, strings of potential dipoles both leading and trailing the current electrode may be used, yielding pole-dipole and dipole-pole configurations simultaneously. The current and potential dipole string(s) are advanced along the survey line, and at each current station measurements are taken at several pulse lengths. The telluric bipole electrodes, T1 and T2,

roughly bracket the roving current and (at least for uniform ground) tend to be of similar potential. The telluric electrodes are moved periodically such that the bipole continues to bracket the current electrode. An orthogonal telluric dipole, located at either end of the telluric bipole, may optionally be used.

In a common operating mode, the telluric electrodes are placed at distances of $1.5\alpha N$ and $2.5\alpha N$ from the current electrode, where α is dipole length and N is the largest η used for the IP line. The current electrode is then advanced toward the telluric electrode $2.5\alpha N$ away, and the telluric bipole is advanced by αN when the current is within $1.5\alpha N$ of that telluric electrode.

The telluric cancelled IP voltage must not contain unacceptable levels of IP and/or EM coupling voltage introduced from the telluric bipole (or remote telluric dipoles). At each pulse length, the telluric bipole (or dipoles) measures an unwanted IP signal component and the desired noise component. Each signal (potential) dipole on the IP line measures the desired signal component and an unwanted telluric noise component. For the telluric cancelled IP value to be valid, the ratio of telluric noise voltage to IP voltage on the telluric bipole (or dipoles) must be very large compared with that ratio on the signal dipole. In general, the telluric bipole or remote telluric dipoles either fulfill this requirement, or can be adapted to fulfill it. A similar requirement holds for EM coupling. Using the telluric bipole, EM coupling will be added or subtracted by the cancellation, but the value is usually not averagely worse than it would have been without cancellation. The same is generally true using the remote telluric dipoles, but each survey case should be considered individually. A detailed discussion of possible signal distortion using telluric cancellation is beyond the scope of this paper.

It was previously indicated that the telluric cancellation relationship given by equation (1) is an approximation. In general, it holds only at a single frequency, and the telluric coefficients A and B should be determined at each data frequency component to properly define the relationship. This would require transformation of time-domain IP data to the frequency domain, with telluric cancellation applied to each of the frequency components in that domain. The data could then either be interpreted in the frequency-domain, or transformed back to the time-domain for interpretation. About 1979, transformation of field data to the frequency domain and telluric cancellation in that domain had been tried on an experimental basis; and it worked. (Perhaps that procedure should be followed routinely.) However, telluric cancellation in the time-domain, without transformation to the frequency-domain, works well also — most of the time. Sometimes, spectacularly so. Possible reasons for this will be discussed below.

TELLURIC CANCELLATION USING IN-LINE BIPOLE

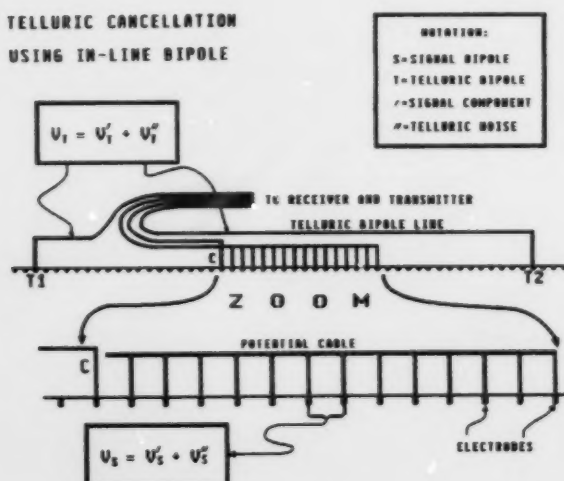


Figure 18.1. Cartoon of in-line telluric bipole (formed by telluric electrodes T1 and T2) used with pole-dipole array for telluric noise cancellation.

The use of frequency-independent telluric coefficients for telluric cancellation of time-domain IP data is valid for a layered earth, even for multiple sources of any frequency content, as long as the telluric bipole (or dipoles) and signal dipoles are over the same layered earth. Consider the telluric cancellation bipole. Over a layered earth, as long as the surveyed line is straight, the telluric coefficient, A , determined for each signal dipole will be the ratio of the length of the cancellation bipole, L , to the length of the signal dipole, α , or $A=L/\alpha$. For bends in the survey line, an orthogonal telluric measurement (coefficient B) will be necessary unless the telluric currents are linearly polarized.

In general, telluric cancellation of time-domain data using frequency-independent telluric coefficients should not work for data taken over a non-layered earth, but there are reasons why in practice it often works quite well. First, telluric coefficients are determined independently for each pulse length used, so these coefficients need be accurate only over a limited frequency band. Second, the telluric coefficients are mostly determined by the frequency components with the largest coherent noise over the period the data are acquired. If these frequency components do not range over too wide a band, the cancellation process will tend to reject them quite well. Fourth, if the telluric cancellation bipole is used, changes in source character or location tend to affect the bipole measurement in a manner somewhat similar to that of the signal dipoles, since the measurements, in part, represent the same geology.

In any event, telluric cancellation using one coefficient, (A) or sometimes two coefficients (A and B) determined at each pulse length is often sufficient for a decade of noise rejection over fairly complex geology. Sometimes it isn't. Telluric cancellation may work well for many minutes (or several hours) and then suddenly work poorly as the character of the telluric source(s) changes. Transformation of data to the frequency-domain and telluric cancellation in that domain would probably improve cancellation in these instances.

DATA PROCESSING

Two key aspects of the data processing will be covered: data compression and the telluric cancellation algorithms. The telluric cancellation process is linear so that the data can be compressed (averaged) "on-the-fly" as they are being acquired, and the telluric cancellation algorithms can then be applied to the reduced data set after acquisition is complete. This is important in real-time telluric cancellation so that processing time and data storage and retrieval requirements are reasonable and commensurate with existing technology. As technology advances, less data averaging before cancellation will allow better

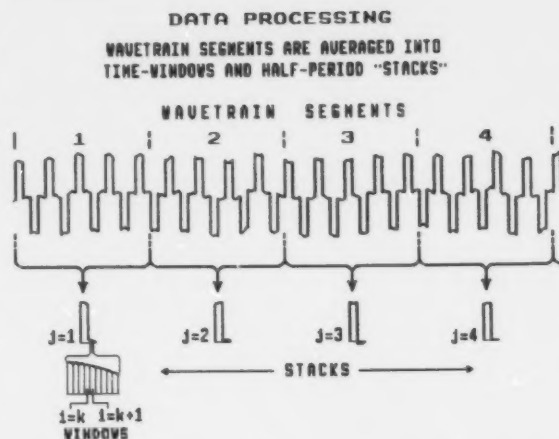


Figure 18.2. Cartoon showing real-time averaging of data from signal dipoles, telluric bipole (or dipoles) and current monitor. Data for wavetrain are compressed into half-period "stacks", with one value per each time-window.

selective stacking and statistical evaluations, and so on.

In the Atlantic Richfield system, at each pulse length, consecutive segments of a wavetrain are averaged (Figure 18.2) on-the-fly into half-period representations which the authors refer to as "stacks", as indicated by a j index. Furthermore, the individual measurements for each stack are averaged on-the-fly into one value for each time window, as indicated by an i index. In this manner, data acquired on 24 channels at 720 Hz and stacked for an hour, say, can be processed in a few seconds, and stored on and retrieved from magnetic tape in a reasonable manner.

In the real-time cancellation of telluric noise from the IP measurements, the data stacks for a signal dipole are processed with those acquired simultaneously on the telluric bipole (or telluric dipoles) to determine the telluric coefficients, A and B ($B=0$ if an orthogonal telluric dipole is not used). The details are as follows. The telluric cancelled voltage for the i th time window of the j th half-period stack is given by the expression:

$$V_{ij} = V_{sij} - [AV_{TXij} + BV_{TYij}] \quad (2)$$

Where V_s denotes the signal dipole voltage, and V_{TX} and V_{TY} denote the telluric dipole voltages. To determine A and B , set a quantity to be minimized as:

$$E = \sum_i \sum_j (V_{ij} - \bar{V}_i)^2 \quad (3)$$

Where $\bar{V}_i$ is the average of the V_{ij} at the i th time window. Next, take the partial derivatives of E with respect to A and B and set them equal to zero, as:

$$\frac{\delta E}{\delta A} = 0, \quad \frac{\delta E}{\delta B} = 0 \quad (4)$$

And solve for A and B.

The signal dipole and telluric bipole (or dipoles) stacks are then linearly combined by inserting the telluric coefficients determined by equation (4) into equation (2), yielding the telluric cancelled stacks. These stacks are then used for the IP calculations and decay curve analysis.

CASE STUDIES USING TELLURIC CANCELLATION

Some case studies are now presented of telluric cancellation applied to deep-looking IP exploration for minerals. The case studies are reworked from materials used for a previous slide presentation (Halverson 1980). The data were acquired with the pole-dipole (or dipole-pole) configuration, using the telluric cancellation bipole without an orthogonal telluric dipole. The IP pseudo sections are plotted in mv/V (millivolts of average decay voltage per volt of pulse voltage). The first part of the decay curve is not used in the calculation, to allow EM coupling to attenuate. The average decay voltage is determined by extrapolation of the average voltage over the time period used to that with a starting time of zero, based on a nominal decay rate (Cole-Cole: $c=2$, $\tau=1$). This is done to normalize the data sets of various surveys.

Thomas Project, Utah

A system with on-board computer and real-time telluric cancellation was initially used at the Thomas Project in Utah. The Thomas is a caldera complex, and possible targets were uranium, base metals or precious metals, with an expected IP response primarily from associated pyrite.

Plate 18.1 (see Colour Folio near back of book) shows an IP pseudo section of part of a line which is herein labeled Line 1. A deep target in intrusives or sediments underlying perhaps a hundred metres of known volcanic units was anticipated. The pseudo section exhibits an apparent pronounced anomaly, flanked on the west by a weak anomaly. Disturbingly, the IP anomalies trend up the current diagonals, which is unusual for the pole-dipole array. Note that some of the plotting points (the dots) are missing; the readings were stacked for 10 to 20 minutes, but data at the missing points still did not meet the percentage-noise cutoff criteria. The same data, same stacking, with telluric cancellation applied are shown in the pseudo section of Plate 18.2. The spurious anomalies have vanished. The pseudo section appears to represent layer-cake geology with modest chargeability values. It shows nothing of interest in a target sense. Note that the missing plotting points have been restored: they now easily meet the per-

centage-noise cutoff criteria. Another similar pronounced spurious anomaly was eliminated farther west on the same line.

A deep, pronounced anomaly was measured on a subsequent line, which will be herein labeled Line 2. The telluric cancelled IP pseudo section at 2.5 seconds pulse length is shown in Plate 18.3. Note that the anomaly is still increasing in magnitude at $\eta=12$. The pseudo section was modeled and interpreted to represent a zone of sulphides that started at 750 m depth, had a width of over 1000 m, and had great strike length orthogonal to line. Telluric cancellation was vital to the interpretation. The uncanceled IP pseudo section at 2.5 seconds pulse length showed the anomaly, but was confused by telluric noise. Also, it was feared that the anomaly might partially represent EM coupling or represent a possible zone of clays. The telluric cancelled IP pseudo sections at 7.5 and 25 seconds pulse lengths showed that the anomaly was real and held up strongly. Based on this, the sulphide interpretation was made. The uncanceled pseudo sections at these pulse lengths were very noisy.

The anomaly was drilled. The drill went into quartzites with latite intrusives and thin bed siltstones at about 150 m depth. Sulphides were encountered starting at about 580 m. A concentrated zone of coarse-grained and interconnected sulphides (10 to 20 percent pyrite) with good silver credits, existed at 730 to 760 m, below which sulphides continued to the bottom of the drill hole (about 1060 m). A second hole was drilled along strike to the south, where the anomaly on a subsequent line became more intense and the source less deep. Unfortunately, drilling through the quartzites was slow and very expensive and the hole was abandoned before it reached the predicted depth of sulphides.

Hall Project, Nevada

The IP system was subsequently used in Nevada to run a survey of several lines in the valley adjacent to the Hall molybdenite deposit. A line herein named Line 1 was run over a section of alluvium up to 600 m thick, containing polarizable clays and zeolites. The target was a molybdenite or copper deposit in a hypothesized large faulted off block of quartz monzonite porphyry at great depth. At least two IP surveys had previously been run by Anaconda Minerals at this prospect. The data had indicated that the alluvial clays and zeolites were strongly polarizable at short pulse lengths, and that the IP response dropped off rapidly as the pulse length was increased. Despite the use of large transmitters and abundant stacking, the deeper-looking IP data had been unusable due to EM coupling, small signal voltages, and telluric noise.

The Line 1 resistivity pseudo section (Plate 18.4) shows that apparent resistivities for $\eta=4-12$ are in the 10 to 20 ohm-metre range (mostly below

15) due to the thick section of alluvial materials. These data indicate that about 2 to 3 seconds decay time would be required to attenuate EM coupling at the large η values. Therefore, long pulse length data must be used. Furthermore, a very long pulse length would attenuate the response of the polarizable alluvial clays-zeolites and allow the IP response of a target molybdenite or copper deposit to show through.

The uncanceled IP pseudo section at 25 seconds pulse length is shown in Plate 18.5. The data were stacked for at least 30 minutes, and noise cutoff criteria are not applied. The pseudo section shows several exceedingly strong IP anomalies, ranging from -120 mv/V to +90 mv/V. The same data, with the same stacking, and with telluric cancellation applied are shown in Plate 18.6. The "anomalies" have now vanished, except for one which trends along the potential diagonals; caused by the drill stem and casing of a hole that was being drilled about 150 m off line as the data were being acquired. Throughout most of the pseudo section, chargeability ranges from 3 to 6 mv/V, which is considered reasonable for the polarizable clays-zeolites at 25 seconds pulse length. There is an IP-high with values up to 21 mv/V which trends up the potential diagonal toward the drill casing label, flanked by an IP-low diagonal to the south. The high is caused by the drill stem and casing, and is a typical response for long metallic cultural features. The telluric cancellation has thus dropped out the noise and left a rather uninteresting response, in terms of the intended target.

Telluric noise cancellation also permits examination of the IP spectra at long pulse lengths. Plate 18.7 shows the percentage ratio of the chargeabilities at the 7.5 seconds and 25 seconds pulse lengths. Throughout most of the pseudo section, except primarily for readings affected by the drill stem-casing, the ratio is quite high, averaging perhaps 125 percent. Inasmuch as the two pulse lengths are only about a half-decade apart in time, this ratio indicates that the IP response is dropping off rapidly with increasing pulse length. This is consistent with the expected behavior of the alluvial clays and zeolites. The IP-high diagonal caused by the drill culture is a ratio low. The ratio low indicates that the IP response would be much larger at very long pulse lengths. This is typical of long metallic cultural features. Aside from drill-stem/casing responses, the high chargeability ratio and the low IP values at the 25 seconds pulse length indicate that a sulphide target was not detected. Such confirmation would not have been possible without telluric cancellation.

HIGH SPATIAL RESOLUTION ARRAYS

We will now move from deep-looking IP to very detailed IP and examine the use of high spatial resolution arrays as a geological mapping tool in gold exploration. The hypothesis is that the use of arrays

with a greater number of measurement dipoles and multiple configurations can provide a more detailed and less ambiguous interpretation of the IP data.

PINSON GOLD MINE, NEVADA

To evaluate this hypothesis and to examine the utility of high spatial resolution arrays in gold exploration, a survey was run at the Pinson gold mine in Humboldt County, Nevada. A highly automated 24 channel IP system developed by the Atlantic Richfield Company, a replacement model for that which was used to acquire the deep IP data presented previously, was used to acquire pole-dipole and dipole-pole data simultaneously. While a roving current moved along the survey line, the system simultaneously measured strings of potential dipoles both leading and trailing the current. The return current was at infinity, generally orthogonal to the survey line. Multiple pulse lengths, ranging from 0.25 to 25 seconds, were used to define the IP spectra.

The data were interpreted using Abhijit Dey's RESIS2D, with some major extensions by Anaconda Minerals. In the modeling process, the pole-dipole and dipole-pole resistivity pseudosections would first be fit, since it is important to match the general current flow patterns through the earth before worrying about matching chargeabilities. The chargeabilities were matched only after obtaining a reasonably good fit to the resistivities. About 30 iterations of forward modeling were done for the line shown.

Repeatedly, it was discovered that the range of models that fit the combined pole-dipole and dipole-pole data sets was much more restricted than that for either data set alone. This had been observed in past surveys: one configuration may couple in better with certain geologic features than the other, and there are sometimes interference patterns on one configuration that are not present on the other. The detail provided by the greater number of potential dipoles was felt to be useful in separating local, near-surface features from deeper ones.

The geologic cross-section for Pinson is shown in Plate 18.8. The following can be ascertained from the pseudo sections and the modeling.

1. The individual ore zones are not evident in the resistivity pseudo section (Plate 18.9) or the IP pseudo section (Plate 18.10).
2. The Comus formation (the ore host) is relatively resistive throughout due to pervasive silicification.
3. A zone of calc-silicate alteration is represented in the model (Plate 18.11) by several resistive bodies. The modeled resistivity pseudo section (Plate 18.12) indicates that this zone is much more pervasive than was indicated on the geological plan map (not shown) and cross-section. This zone of calc-silicate alteration is bounded by a major structure on its eastern side.
4. The Vinini formation is extremely conductive and chargeable at depth. The difference in cou-

pling between the dipole-pole and pole-dipole arrays, as indicated by the greater chargeability on the dipole-pole array, imply a dipping contact to the east with the Comus formation. The Venini formation has been silicified along its contact with the Comus formation. This may explain the discrepancy between the location of this boundary as shown in the geologic cross-section (station 19.5) and as interpreted in the modeling results (station 22).

5. The geology in the area of the Preble-Comus contact is not well known, that is, the geologic cross-section may not be accurate there. The geophysical model indicates more complexity than the simple contact shown in the geologic cross-section.

In summary, the Pinson survey demonstrated that detailed IP and resistivity could be useful as an indirect geological mapping tool in gold exploration.

QUARTZ MOUNTAIN GOLD DEPOSIT, OREGON

The system was also used on an exploration project at the Quartz Mountain gold deposit, which is a volcanic hosted, paleo-hot springs type deposit, owned by Wavcrest Resources, Incorporated. Wavcrest reports that it contains more than one million ounces of gold.

Several lines were run and modeled in detail, but the authors had only the data for Line 1 at the time of writing. This line traverses the center of the hot springs activity. Data collection was similar to the Pinson survey: both pole-dipole and dipole-pole data were simultaneously collected.

The two chargeability-high anomalies (Plate 18.13) are caused by gold-bearing units containing pyrite. The character of the west anomaly (station 6) is different for the two arrays: the west unit couples better with the dipole-pole array. Modeling results suggested that this is due to an eastward dipping source. This was confirmed by drilling. The body representing the east chargeability-high anomaly (stations 22 to 26) couples best with the pole-dipole array. The preferential coupling and the modeling indicated a westward dipping body. This interpretation was also confirmed by subsequent drilling.

Spectral data (not shown) were acquired for pulse lengths ranging from 0.25 to 25 seconds. Spectral differences between the east and west chargeability highs are not obvious using data at 2.5 seconds pulse length or shorter. However, the spectra at 25 seconds pulse length are distinctly different: the east anomaly exhibits much larger Cole-Cole time constants. An interpretation was made that the east vein contained sulphides of much coarser texture. Subsequent core drilling intersected a gold-bearing unit with micro-fine disseminated pyrite related to the west anomaly. Pyrite in veins up to one

half inch thick was intersected by drilling at the east anomaly.

Holes drilled on several IP anomalies detected on subsequent survey lines intersected gold-bearing units containing pyrite.

Finally, a tie-in can be made with telluric noise cancellation. Line 1 was run without telluric cancellation. Acquisition of high quality data to 25 seconds pulse length required about one hour per current station. For subsequent lines (not shown), telluric cancellation using remote orthogonal telluric dipoles and digital radio telemetry was employed. Telluric cancellation reduced the stacking time to about 10 minutes for equally high quality data.

CONCLUSIONS

As indicated in the Introduction, this paper has focussed on two aspects of IP technology: telluric noise cancellation and high spatial resolution arrays. The following conclusions can be made regarding telluric noise cancellation:

1. Minerals exploration case studies show that telluric noise cancellation can provide valid IP data, even broadband IP data at very long pulse lengths, for deep targets in conductive environments, where signal-to-noise would otherwise be prohibitive.
2. Several configurations can be used for telluric cancellation. Remote orthogonal telluric dipoles with digital telemetry to the IP survey line is one such configuration. A hard-wired telluric bipole (with or without an orthogonal telluric dipole) for use with the pole-dipole configuration is another. Other hard-wired telluric configurations would be suitable for dipole-dipole.
3. Telluric cancellation in the time-domain, using the telluric cancellation bipole and a single telluric coefficient at each pulse length (two coefficients if an orthogonal telluric dipole is used), has worked well for most surveys; sometimes spectacularly so. But for some surveys it has worked marginally or not at all. Transformation of the data to the frequency-domain, with telluric cancellation in that domain, would probably improve telluric cancellation for these surveys.

The following conclusions are made pertaining to high spatial resolution arrays and surveys using them:

1. For high quality data, there would appear to be a descending order of information content from pole-pole, through pole-dipole to dipole-dipole, since the latter can be derived from the former but the reverse process does not hold. The utility of this information increment is not well defined.
2. Similarly, there is greater inherent information content in pole-dipole and dipole-pole data

sets, interpreted together, than in either data set interpreted separately. One array often couples better with components of the geology than the other, and there may be anomaly interference patterns with one array that do not occur with the other.

3. High spatial resolution arrays using pole-dipole and dipole-pole were exploited at the Pinson gold mine, Nevada, to aid detailed geological mapping. The survey mapped zones of calc-silicate alteration in the ore-host formation, as well as the major geologic features. In modeling the data, the requirement to fit the data sets of both arrays gave a less ambiguous, more definitive interpretation.
4. An exploration survey at the Quartz Mountain gold deposit showed the utility of detailed broadband IP data acquired with the two configurations. The IP data detected and correctly predicted the direction of dip of two flat-dipping gold-bearing veins containing pyrite. The broadband IP data at 25 seconds pulse length correctly indicated sulphide-texture differences between the two veins. Both findings were subsequently confirmed by drilling.

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19. Inverse Methods in Geophysical Exploration

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ABSTRACT

Many computer program packages are now available for "inverting" geophysical data, i.e. for finding model configurations of the Earth's physical properties such that the predicted geophysical response of the model is similar to the data recorded by the geophysical survey. Different approaches to inversion are possible. These range from classical graphical, and more modern computer-based techniques of solving directly for a small number of model parameters from a similar number of observational data; through computerized iterative optimization methods that use least squares fitting of the observed and predicted data to find the parameters of a "best fitting" model; to search techniques that explore the ambiguity of interpretations by finding suites of different types of model that all fit the observational data. Iterative least squares optimization is widely used in magnetic and gravity model fitting and in the interpretation of electrical soundings, and is now often implemented on personal computers. Direct inverse methods now are routinely applied to airborne and ground electromagnetic traverse data to estimate conductivity layering. A difficulty with all inversion methods is that all geophysical interpretation is fundamentally ambiguous. The answer obtained may depend strongly on initial assumptions and on details of the specific inverse method; furthermore, describing the possible errors in an inversion is a difficult and ill-defined task. Inversion is always a balancing act in which the desire to extract as much information as possible from subtle, but possibly error-contaminated, aspects of the data must be traded off against the risk of inferring completely illusory earth structure. Despite the great improvements in methodology, a user still needs a clear understanding of fundamentals if he is to appreciate what an inversion is telling him about the Earth. In this paper, we review some of the basic concepts and the problems implicit in geophysical inversion, and describe some new approaches which have already been tried experimentally.

INTRODUCTION

Successful interpretation of geophysical data requires knowledge of three different elements. First, the influence of the Earth's physical properties on the geophysical observables must be understood; that is, a physical modeling capability must exist. As

an example, the relationship between density anomalies and gravity anomalies must be formulated explicitly in order that gravity data can be modeled. Second, there must be an understanding of how physical properties are controlled by the geological parameters of the rock. Continuing the example above, the dependence of density anomalies on mineralogy and porosity must be known, and the relationship between local rock mineralogy and porosity, and the overall geological structure of the area should be understood. Finally, to restrict the enormous range of possible models somewhat, there must be an understanding of what geological features could reasonably be present. The first of these is clearly a geophysical task, the last a geological task, while the second lies between. The concern of this paper is only with the first of these problems, and with the solutions which have collectively come to be known as inverse theory.

The relationship between the distribution of physical properties in the Earth and the geophysical observables can be looked at in two ways. Inference of the observables from the properties is called the forward or modeling problem and the opposite is called the inverse problem. The former is how one initially learns the nature of a problem, because it is easier, but the latter is what has to be done in real interpretation. In forward modeling, a simplified model of the Earth is used to predict observable data, which may then be compared with actual observations. If the simplified model is a reasonable fit, it is assumed to resemble the real Earth in some sense, although clear assessments of exactly what this sense is have only been developed in geophysics during the last two decades. The reason for working with simplified models is twofold: first, the real Earth is always too complicated to be fully described in a feasible model, and certainly it is too laborious to construct models for testing that have vast detail in them. Second, it usually turns out that much of the detail has no appreciable effect on the geophysical observables and is therefore incapable of definition by the data.

When computer-implemented inverse methods first appeared, they made it possible to use models of greater detail than was practical previously, and many geophysicists were tempted to use such detail, forgetting that the second reason was as strong an argument as ever against too-complex models, however easily generated. Exercises in overinterpretation

were in fact fruitful, because they led to a clarification of the goals of inverse theory. There are several different questions one can ask. What model structure is appropriate for fitting the data? What common properties (numerical or otherwise) do all models that fit the data have in common? Finally, (if one is still bold enough to ask) what are the numerical values of the model parameters of some selected type of model that one has decided are of interest?

In this paper, we shall always assume that the forward modeling problem is possible, and, at least in principle, is not difficult to implement. We shall discuss principles rather than the ease of or methods for implementation, except where some feature of the problem makes implementation impossible. Examples will be drawn from a small subset of the actual applications; the object here being to review principles rather than provide an historical bibliography of geophysical inverse theory. The examples shown are partly drawn from the published literature and partly from work in our own group.

CLASSIFICATION OF MODELS

Formally, the nature of the questions one can ask of a geophysical data set and the way in which one may seek answers depends on the relative dimensions of the data set and the model parameters. If the model used is simple enough that it has fewer parameters than there are data, the model is said to be formally overdetermined and methods based on achieving a best fit to the data are used. If the model has more parameters than the number of data, the model is formally underdetermined, and decisions must be made about which of an infinite number of models that could fit the data should be presented. In this latter class are models in which parameters are represented by a continuous function of position, which is equivalent to an infinite number of parameters.

The dividing line between the formally overdetermined and underdetermined cases is the evenly determined case. The dividing line is not so clear in practice as it is formally. Lack of independence between the data often causes effective underdetermination, even for models far less complex than one might imagine. Nevertheless, the evenly determined model is a useful concept for very simple models with small amounts of data.

In all this, it must be emphasized that whether the model is overdetermined or underdetermined is not a real property of the physical situation; it is a consequence of decisions on the part of the interpreter about how far to simplify the model or (equivalently) how much *a priori* information to incorporate into the model, whether correct or not!

EVENLY DETERMINED MODELS

DIRECT INVERSION: THE METHOD OF CHARACTERISTIC MEASURES

The simplest approach to inversion, and one that has been in use for decades, can be applied in cases where a simple model with only a very small number of parameters (n), is to be fitted to the data. Construction of the inversion procedure proceeds as follows: After a preliminary but thorough examination of how model data vary with changes in the model parameters, n , "characteristic" measures of the data are identified which quantitatively describe the significant aspects of the model data. The relationship between the model parameters and the data characteristics is then systematically mapped using the forward modeling capability. Then a method (usually graphical) is found by which the multidimensional map can be used to go in the opposite direction, from data characteristics to model parameters.

The simplest possible example of this sort of direct inversion is fitting of a spherical density anomaly to a bulls-eye type of gravity anomaly. The model parameters are: $\Delta\rho$, the anomalous density; a , the sphere radius; z , the depth to centre; and x, y , the horizontal position of the centre. A preliminary examination reveals immediately that $\Delta\rho$ and a have no separate effect on model data and should be reduced to a single parameter $\Delta m = 4\pi a^3 \Delta\rho/3$, the anomalous mass. Also, the centre point of the sphere always lies directly under the peak of the model anomaly. Thus, x, y can be found independently of other parameters. Then, the two remaining parameters (the anomalous mass and the depth to centre) can be very simply related to the intensity and width of the anomaly by characteristic measures such as the peak value and the half width, or the ratio of peak intensity to maximum anomaly gradient. The result is the well known "rule of thumb":

$$z = \frac{\left(\begin{array}{c} \text{anomaly width at} \\ \text{half peak amplitude} \end{array} \right)}{1.54}$$

$$\text{or } z = \frac{0.85 \Delta g_{\max}}{\left(\frac{d\Delta g}{dx} \right)_{\max}}$$

$$\text{and } \Delta m = \frac{z^2 \Delta g_{\max}}{G}$$

This approach to inversion was of great importance when data interpreters had little personal access to substantive computing power. Extending it to less trivial cases than the above example requires an astute selection of model parameters and data characteristics, and the method was brought to a culmi-

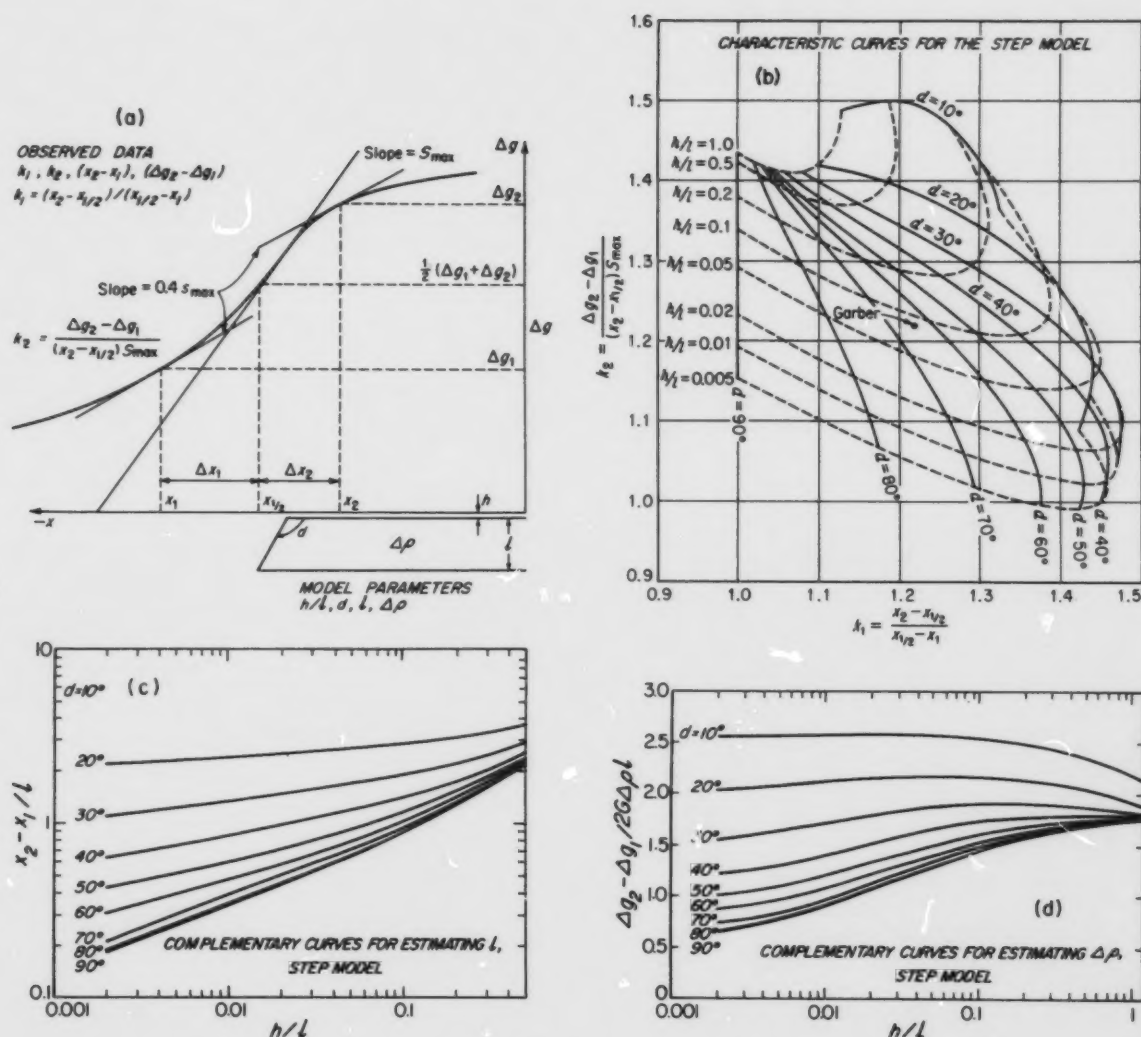


Figure 19.1. The gravitational two-dimensional step model (after Grant 1965): a) data characteristics and model parameters defined; b) dimensionless data characteristics k_1 and k_2 plotted as a function of dimensionless model parameters d and h/l (except for scaling parameters, this model has only two characteristics and two parameters, so the graph displays a complete map of the relationship between the data and model vectors); c) and d) complementary curves which establish the scale parameters of the step model once its dimensionless parameters are known.

nation by F.S. Grant who designed procedures for a variety of simple gravity and magnetic models (e.g. Grant and West 1965). An example of his procedure for a density step model is shown in Figure 19.1. It is reviewed here because it illustrates, in a clear graphical form, several basic features which underlie all interpretation problems.

The two-dimensional step model has four parameters in addition to the position of the upper

edge of the step with respect to the gravity profile. Two are dimensionless geometrical quantities (the dip and the ratio of depth-to-top to depth-extent), the other two are of necessity dimensioned (density contrast and depth-extent). Corresponding to these, four data "characteristics" are selected: two dimensionless measures of profile shape, and two measures of scale (Figure 19.1a). From dimensional considerations, and the basic form of the gravitational attraction law, one sees that the relationship between

data characteristics and model parameters must be in the form

$$\begin{aligned}k_1 &= F_1(d, h/l) \\k_2 &= F_2(d, h/l) \\x_2 - x_1 &= lF_3(d, h/l) \\ \Delta g_1 - \Delta g_2 &= \Delta \rho F_4(d, h/l)\end{aligned}$$

where the F s are dimensionless functions of the dimensionless parameters.

They can be tabulated quantitatively with the aid of a forward modeling algorithm, and the first pair of equations can be charted on a single graph (Figure 19.1b) which completely defines the mapping relationship between k_1 , k_2 and d , h/l . In inversion, d and h/l are found from k_1 and k_2 , and the second pair of functions F_3 and F_4 , and then used to find the scale parameters, l and $\Delta \rho$ (Figure 19.1c).

The mapping relation shown in Figure 19.1b demonstrates several key features of inverse problems which are shown schematically in Figure 19.2. Firstly, in many parts of the map, the relationship

between the characteristics and the parameters is simply a coordinate transformation which locally is approximately uniform (i.e. linear) (Figure 19.2a). Looking on a larger scale, the mapping is seen to be non-linear, as it changes from place to place in the map, the parameter estimate being less orthogonal in some areas than in others (Figure 19.2b).

The mapping is usually confined to a bounded domain because the model parameters and data characteristics have natural limits to their range. Furthermore, it may not extend everywhere within the permitted value ranges of the characteristics, as some values of the data characteristics cannot be realized by any values of the model parameters (Figure 19.2c). Also, the mapping is not single valued. Then there may be regions where more than one point (i.e. pair of values) in the model parameter space corresponds to a given point in the data characteristic space. Particularly at boundaries where the mapping folds over on itself, but possibly also in other regions, the locally approximately uniform coordinate transformation may degenerate. The coordinate lines of two parameters may become parallel to one another rather than crossing at an appreciable angle and/or they may become strongly curved. In such regions (e.g. A-A' in Figure 19.2c), an area of parameter space maps not to an area in data space, but to a line segment, and the data-to-parameter mapping becomes ambiguous there. The sphere model provides an extreme example. An area in $\Delta \rho$ - a space would map into a line in any data characteristic space, because only the combination of the two parameters (in the form of Δm) affects the observational data.

In summary, a nonlinear mapping from one n -dimensional space to another may not everywhere be straightforward. Usually, it is difficult to find a single set of data characteristics that will map more or less uniformly and with reasonable orthogonality into the parameter space throughout the whole interesting range of model parameters. Different choices of data characteristics and a different parameterization of the model may be required in different parameter regions. Also, graphical mapping is only straightforward in two dimensions. A higher-order mapping can only be graphed as two-dimensional cross-sections or projections of the higher-order space. Sometimes it is possible to find parameters and characteristics such that the parameter surfaces in characteristic space are approximately cylindrical, so that the mapping can be described by one or a few two-dimensional cross-sections. However, complete graphical or tabulated mappings are feasible at best, only in three or four dimensions, so only very simple models can be handled in this manner. Nevertheless, one must keep in mind that there are very many cases in which use of a simple model will extract almost all the information which can be obtained from the data. Although more complicated models might in principle extract more, appropri-

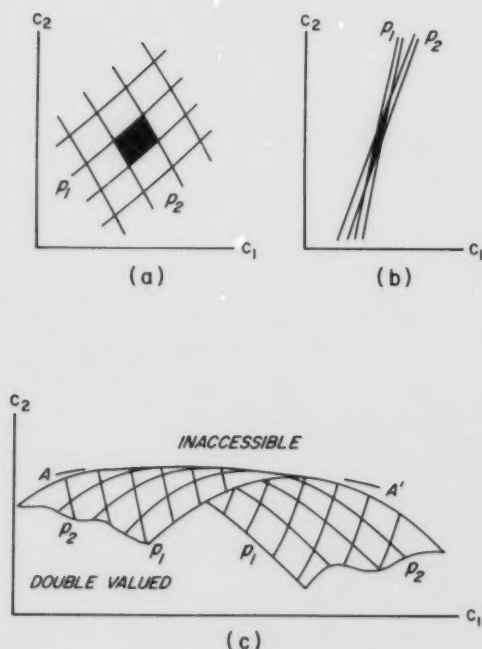


Figure 19.2. Schematic diagram showing features of an evenly determined mapping relationship between a pair of data characteristics c_1 and c_2 and model parameters p_1 and p_2 : a) a normal, well-conditioned region in the mapping; b) a region where the parameter coordinates are nearly collinear with respect to the characteristic coordinates making the mapping prone to error; c) a region where the mapping becomes complicated and double valued. At the fold line A-A', an area in parameter space degenerates to a line in characteristic space.

ately complicated models are often beyond our present ability in forward modeling.

ERROR AND MISFIT

The concept of representing the observational data (or quantities such as anomaly characteristics which are directly derived from it), and the free parameters of the model as points or vectors in multidimensional vector spaces is important. However, inversion is not simply a matter of mapping from a data space to a parameter space. Even if we knew the parameter values of a model which would optimally represent the real Earth at the location of interest, we would not expect synthetic observational data for that model to match the real observations exactly. Firstly, all observations have limited accuracy because of experimental limitations. Secondly, the model is always a grossly simplified picture of real earth structure and it usually represents that structure only within a limited region. Thus, some misfit would be expected even if the observations were perfect; the amount and kind being dependent on the interpretation problem. We shall refer to the first type of misfit as *observational* or *data error* and the second as *model error* or *geological misfit*. Because geological misfit is unlikely to be a discrepancy which is random and uncorrelated from one observation to another, the term "geological noise" which is sometimes given to it can be misleading.

If error limits can somehow be estimated for the data (or related characteristics), the n parameter direct inverse problem becomes one of mapping an n -dimensional region (rather than a point) in the data space, to an n -dimensional region in the model space. The size and form of the region in model space then provides an estimate of possible error in the inversion.

OPTIMUM FITTING

In a practical inversion problem, it is generally difficult to know the dimensionality of the observational data, i.e. how many independent pieces of information it contains. In abstract, the dimensionality is equal to the number of measured data which provide independent information about the model, but, in practice, multiple observations often serve as much to reduce and quantify the error in estimating some sort of mean observations as to each give independent information. For example, adjacent observations on a profile often serve as much to enable drawing of a smooth average response profile free of local site effects as they do to provide independent data about structure at depth. Also, data to be used in the inversion may themselves be derived from other more basic observations (e.g. contoured or gridded data interpolated between recordings on a continuous flight line profile) in a way that makes it hard to recognize independence.

In direct inversion by characteristics, the number of characteristics is arbitrarily set equal to the number of model parameters to be determined; and it is assumed that the number of observational data is more than adequate to define data characteristics to satisfactory accuracy. Thus, some sort of averaging or editing will usually be involved in calculating them from the original data. When the inversion is complete, all that is assured is that the model data will have the same characteristics as the field data. If a complete set of model data is then calculated and compared to the original field observations, some discrepancy is likely. The discrepancy will likely be minor if the basic form of the model on which the inversion was based was appropriate to the real geology. But if a poor choice was made, it is quite possible for the correspondence to be poor.

The above problems suggest that inversion could fruitfully be a fitting process in which synthetic observations calculated for the optimum model are directly compared with the actual field observations by some sort of optimization process.

The difficulty of displaying more than a few parameters this way limits the usefulness of the method. Also, the restriction to exactly determined models is artificial and restrictive; modern techniques for analyzing problems such as singular value decomposition allow the "careful choice" of data characteristics to be automated to some extent and done separately for every problem solved, regardless of whether the problem is overdetermined or underdetermined.

OVERDETERMINED MODELS

In this approach we consider the inverse problem to be one of adjusting a relatively small number of model parameters until a "best fit" to a larger number of data is obtained. The sense in which the fit is "best" is usually the minimum sum of squared errors (least squares); error being the difference between observed and model data. This choice is primarily for convenience because it leads to solving a linear rather than a nonlinear set of equations for the model parameters. Although it can also be shown that least-squares modeling is optimal in a maximum-likelihood sense if the errors of the model have a Gaussian or Normal probability distribution, this theoretical justification for least-squares methods is often not supported by the nature of the geophysical inverse problems and the data. Were it not for the added theoretical and computational complexity associated with them, "robust" methods of fitting (e.g. Claerbout and Muir 1973; Mosteller and Tukey 1977; Huber 1981) that rely less on the above assumptions about data would rightly enjoy greater popularity.

In most inverse problems of interest, the relationship between the data and the model parameters is nonlinear. (One of the few exceptions is a gravity

or magnetic model where the model parameters are the anomalous density or susceptibility in cells of fixed position.) An iterative approach to fitting the data is then required, based on repeated linearizations of the problem about the current best solution, until a stable solution is reached (if possible). That is (assuming all data to be equally good), one minimizes:

$$|d - m|^2$$

where d = vector of observed data, and m = vector of data computed for the presumed model which is described by a vector p of model parameters. To do this, one approximates the nonlinear relationship of data to model parameters by truncating a Taylor series expansion of the observables in terms of the model parameters p about a trial model $m^{(k)} = m(p^{(k)})$, as in

$$m \doteq m^{(k)} + \left(\frac{\partial m}{\partial p} \right)_{p^{(k)}} (p - p^{(k)})$$

$$i.e. \quad y = Ax$$

where the vectors y and x and the matrix of partial derivatives A are defined by

$$\begin{aligned} y &= m - m^{(k)} \\ x &= p - p^{(k)} \\ A &= \left(\frac{\partial m}{\partial p} \right)_{p^{(k)}} \end{aligned}$$

The dimensions of the vectors y and x are m and n respectively with $m > n$, and the matrix A is m by n in size.

The formal solution of the above minimization problem is the textbook result (e.g. Searle 1971; Draper and Smith 1981; Menke 1984) for parameter estimates $\hat{x}$ in a multivariate linear regression problem, namely

$$\hat{x} = (A^T A)^{-1} A^T y$$

$A^T A$ is a square matrix of size n , which, in the case where $n < m$, can usually be inverted to yield the least-squares multivariate linear regression estimate of x . It is worth noting that this is also denoted as the best linear unbiased estimator (BLUE), when derived from a somewhat different starting point (Searle 1971). The parameter estimation variances are related to the data error variance σ^2 by

$$\text{Var}(\hat{x}) = (\hat{x} - x)(\hat{x} - x)^T = \sigma^2 (A^T A)^{-1}$$

(A more complicated formulation of the inverse and the error estimates to provide weighting factors is required if data variances are not all the same.)

If the problem is truly overdetermined, this formal solution is also a practical solution. However, if the problem is underdetermined in a formal (or practical) sense, this is equivalent to exact (or approximate) vanishing of the determinant of $(A^T A)$. This means, of course, that the inverse $(A^T A)^{-1}$ does not exist (or is very badly determined), and, as can be seen from the parameter estimate variance formula, the parameter estimation variance tends to infinity.

One way of forcing the solution to be calculable (which is not the same as being correct), is simply to alter $(A^T A)$ to a slightly different, more diagonally dominant matrix (and as it turns out, an invertible matrix) by adding a positive constant α all along the main diagonal to give

$$(A^T A + \alpha I)$$

This description of the procedure makes it seem a little arbitrary, but it turns out that the resulting solution for the parameter estimates, namely

$$\hat{x} = (A^T A + \alpha I)^{-1} A^T y$$

is the least-squares best estimate subject to the constraint that the mean square parameter estimate not exceed a specified value (a value inversely related to α). This method is known variously as Ridge Regression or Damped Least Squares (Hoerl and Kennard 1970; Marquardt 1970; Vozoff and Jupp 1975), also the basis of the iterative solution corrections in the Marquardt-Levenberg algorithm (Levenberg 1944; Marquardt, 1963), a popular implementation of iterative least-squares. It does not make the estimates of those parameters, which are genuinely indeterminate, any better, but it restricts (damps) their wild excursions to a maximum size implicitly preset by α , while having little effect on well determined parameters (for which the relevant column of $A^T A$ is probably diagonally dominant already to an extent that the added term has little influence). More to the point, the procedure permits numerical inversion of $(A^T A + \alpha I)$ so that the well determined parameters, if any, can actually be estimated.

Often no individual parameter can be well estimated, but certain combinations of them can. This is the motivation for the use of the Singular Value Decomposition (SVD) method (e.g. Wiggins 1972; Jackson 1973), which does not get a better solution than the above method, but clarifies the nature of the information given about the parameters by the data. By methods (Lawson and Hanson 1974; Wiggins 1972; Lanczos 1961) that we will not detail here, it is possible to find linear combinations (eigendata) $y' = U^T y$ of the original data y , and linear combinations (eigenparameters) $x' = V^T x$ of the original parameters x , such that the relationships be-

tween these new quantities are the extremely simple ones

$$y_i' = \Lambda_i x_i' \quad \text{for } i = 1 \text{ to } n$$

where the Λ_i are called the singular values (for $n = m$, these are the usual eigenvalues of the now square matrix A). The linear combinations involved are all orthonormal vectors of weights, so that the errors of the eigendata have the same variance as the original data. It is then clear that the errors in eigenparameters corresponding to small singular values are very large, as they arise from dividing the eigendata errors by a small Λ_i . If the original data are pre-normalized so that their errors have unit standard deviation, as is often done in problems of this sort, then the standard deviations of the errors in the eigenparameters are simply the reciprocals of the corresponding singular values Λ_i .

If the damped inverse solution is recast in these eigenvariables as

$$\hat{x}_i' = \frac{\Lambda_i x_i'}{(\Lambda_i^2 + \alpha)} \quad \text{for } i = 1 \text{ to } n$$

the way in which damping works is somewhat clearer: the amplification of error by division by a small Λ_i is suppressed, necessarily at the expense of introducing a downward bias in the size of parameter estimates. This bias is desirable as it actually accords with our preconception that parameter sizes above a certain level are unreasonable, regardless of what the (possibly) erroneous data suggest. (Note that "parameter size" in the iterative problem actually corresponds to the change in the parameter from the previous model.) Incorporation of this type of bias in a more sophisticated way is in fact the basis of another derivation of the damped least squares estimator above, under the name Stochastic Inverse which is discussed later in this paper.

The above is not, however, the main point of the SVD method. The main point is the formulation of the simple relationships above, which tell the interpreter which linear combinations of the data are in fact well determined by the data. Figure 19.3, taken from Inman (1975), shows an example of this for a synthetic Schlumberger VES (vertical electric sounding) resistivity inverse problem, where the model consists of two layers over a half-space. The eigenparameters of the solution are shown schematically in Figure 19.4. The eigenparameter with the third largest singular value (and thus the third best determined) is primarily the resistivity of the bottom half-space. The two worst determined eigenparameters are the sum of the fractional changes in resistivity and thickness of layer one, and the difference of the fractional changes in the resistivity and thickness of layer two. These badly determined eigenvectors represent the changes in the model which least affect the fit to the data. If a small up-

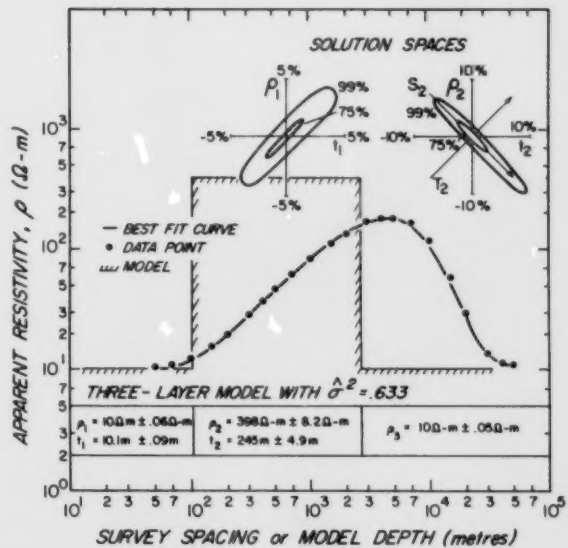


Figure 19.3. A test of inversion of a Schlumberger (VES) electrical sounding by the damped least squares method (ridge regression), taken from Inman (1975). The data are synthetic, for a two layer and half space model with resistivities 10, 390, and 10 ohm-m and thicknesses of 10 and 250 m with 1 percent random noise added. The starting model had resistivities 8, 500, and 5 ohm-m, and thicknesses of 15 and 150 m. The algorithm converged rapidly to an excellent solution. Contours of the fitting error for variations in the thickness and resistivity of each layer are also shown.

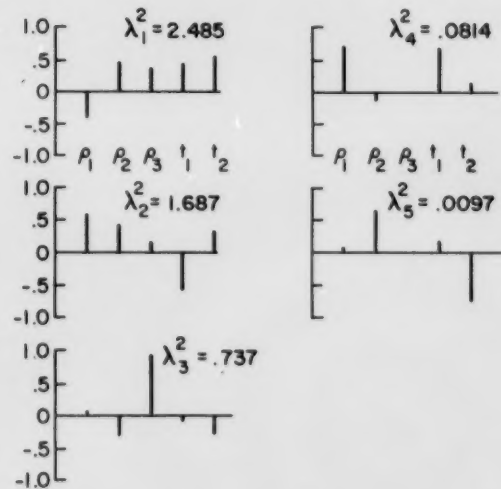


Figure 19.4. Components of the eigenvectors of relative parameter changes and their eigenvalues, for the solution shown in Figure 19.3 (from Inman 1975). Note that the most poorly determined eigenparameter corresponds approximately to parameter changes which do not alter the $\rho_2 t_2$ product, a well known ambiguity for a highly contrasting resistive layer.

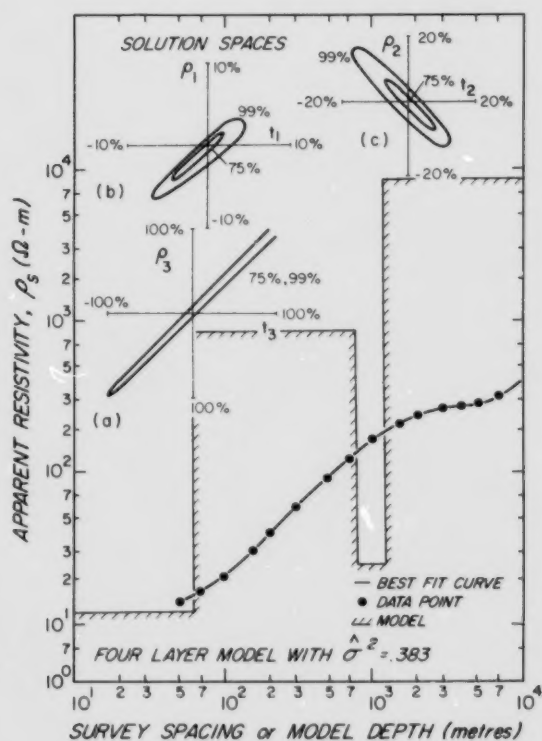


Figure 19.5. Inversion of another synthetic VES sounding, from Inman (1975). In this test, the data are from a three layer and half space model in which the third layer is almost hidden. No noise was added to the data, but iteration was stopped when the error of fit became comparable to the noise added in the previous test. Relatively strong damping was required to prevent instability, as one of the parameter eigenvalues was negligibly small. It corresponds to ambiguity in layer three, where changes that do not alter the layer's conductivity-thickness product have no effect. The presence of badly determined eigenvectors makes error estimates on the individual parameter values almost meaningless. Instability in estimating the layer three parameter values was prevented by the damping which kept them near the starting values. Parameters of the test model were resistivities 12, 840, 24, 8400 ohm-m and thicknesses 6, 72, 48 m.

ward change in resistivity occurs in layer one, but is compensated by a downward change in the thickness, the fit to the data is left effectively unchanged. The two best determined eigenparameters are clearly rather complex combinations of the original parameters; SVD here shows that the badly determined parts of the model are rather more simply described than the well determined parts.

Figures 19.5 and 19.6 show two more examples of VES inversion; one a difficult-to-resolve synthetic model, and the other a field example. Damping was essential in these cases to maintain convergence in spite of ambiguities in the models.

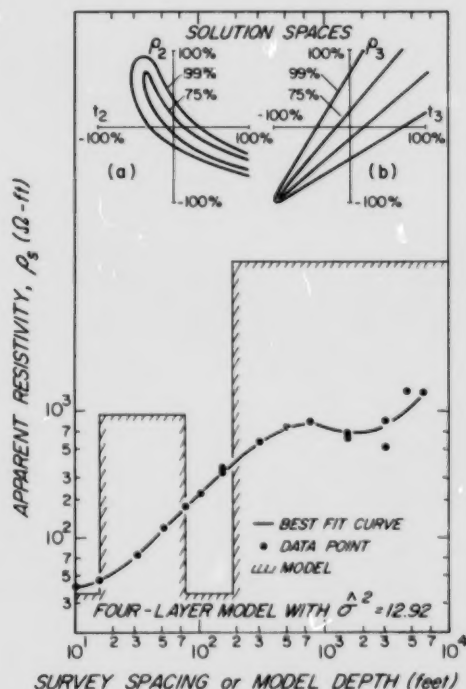


Figure 19.6. Inversion of a real VES sounding, from Inman (1975). There is substantial ambiguity in determining the parameters of layers two and three. Large parameter changes which preserve the resistivity-thickness product of layer 2 and the conductivity-thickness product of layer 3 are admissible. Note that error contours for changes in ρ_2 , t_2 and ρ_3 , t_3 about the solution point are not elliptical and therefore are poorly described by linearized analysis.

AMBIGUITY AND MODEL ERROR

The nature of the ambiguities in the solution is shown clearly (and also independently of the method by which the solution was obtained) by directly calculating the error with the forward modeling algorithm for a region in parameter space around the solution. Inman has done this for the pairs of the worst determined parameters in the three examples. In Figures 19.3, 19.5, and 19.6, contour diagrams of the error surface are shown as insets. The error contours have a more or less elliptical form about the minimum. In the linear approximation, which generally is accurate near the minimum, the error contours will be (hyper)ellipses in spaces with the same number of dimensions as there are model parameters. The eigenparameter vectors provided by SVD analysis give the directions in parameter space of the principal axes of the ellipses. The axis lengths are inversely proportional to the corresponding eigenvalues.

Convergence to an optimum solution is much faster, and error analysis is greatly facilitated, if the

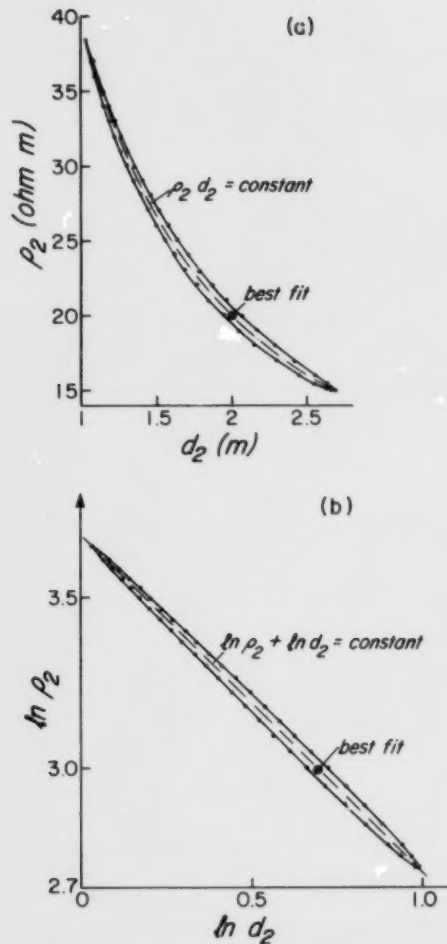


Figure 19.7. Plots of fitting error in a VES inversion in which there is a strong resistivity-thickness ambiguity. The graphs compare the use of resistivity ρ and layer thickness d as parameters; a) with use of $\ln \rho$ and $\ln d$ (b). Logarithmic variables make the error contours much more nearly elliptical, so the linear approximation used at each step in the inversion is valid over a larger range. This is particularly important when error estimates are made by linear analysis (from Johansen 1977).

inverse problem is linear in a large area around the solution. Linearity can often be strongly affected by the choice of model parameters. In the case of VES inversion, Johansen (1977) has provided a nice example of linearization by using logarithmic model parameters, $\ln(\rho_i)$ and $\ln(t_i)$. The improvement is shown in Figure 19.7. Not only is a linearization achieved, but the physical requirement of resistivities and thicknesses only being positive is assured at the same time.

Even when a linear approximation is valid, it can be difficult to describe the error limits of an inversion. There is no single correct way of presenting the

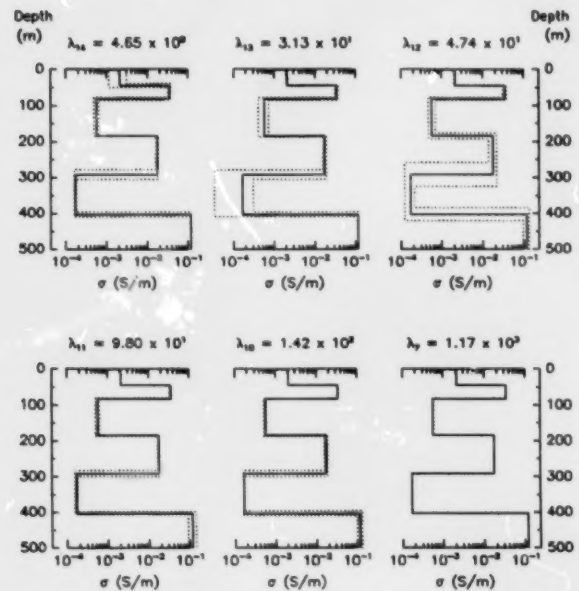


Figure 19.8. An example of how the error limits in a layered earth conductivity sounding can be displayed independently for each eigenvector. The dashed lines show the envelope of model perturbations resulting if each eigen-parameter is allowed to fluctuate over its probable range of values. Independence of the terms is the virtue of this display. The errors associated with the better determined eigenvectors are unaffected by decisions on whether the more poorly determined terms should be considered free variables in the inversion or should be set by a priori information. The example is from a grounded source EM sounding survey (Boerner 1987).

information. One of the most straightforward is to show graphically the error ranges corresponding to each eigenvector on a separate picture of the model. An example from inversion of an elaborate EM sounding is shown in Figure 19.8. Another approach which is appropriate when the overall error in the estimate of a specific parameter is required, is indicated schematically in Figure 19.9. To find the error range in one particular parameter, one must consider the possible contributions from all eigen-parameters' components. One must also note that the extreme parameter values calculated this way imply certain compensating changes in all the other parameters which minimize the misfit that otherwise would arise. This can be illustrated by plotting separate error vectors for each parameter much as in Figure 19.8, but showing in addition to the extremal error in that parameter, the compensating changes in the other parameters.

Often there may be a highly arbitrary aspect to error estimates for individual model parameters. An example is given by Johansen (1977). If the number of free parameters in the model is made larger, the solution will undoubtedly come to a point where an

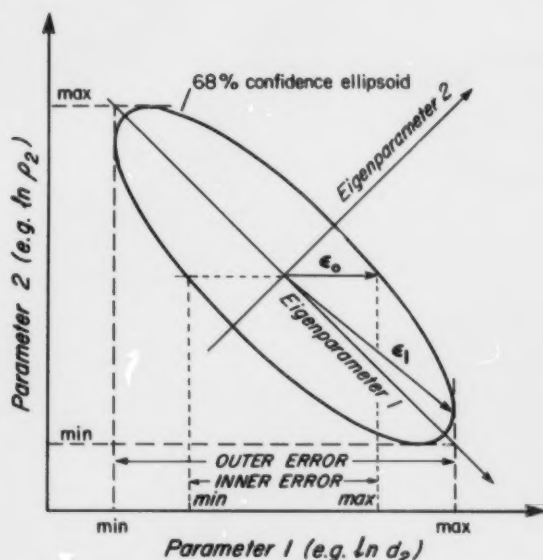


Figure 19.9. Showing schematically the different ways of describing error limits in a multivariate solution. The error can be described either by the length and direction of the axes of the error (hyper)ellipsoid, i.e. by eigenvectors and (inverse) eigenvalues, or instead by error ranges on the individual parameters. Two measures of parameter error are meaningful, an "inner error" ϵ_0 which is the amount parameter 1 can change if no other changes are made in the model, and an "outer error" ϵ_1 which is the maximum amount the parameter can be altered if compensating changes are introduced in other parameters. The latter error may be much larger if the parameter is in any way involved in a serious ambiguity.

important ambiguity is introduced, i.e. where the eigenvalue corresponding to at least one of the eigenvectors becomes unacceptably low. The error estimate of any model parameter which has an appreciable component in that eigenparameter will then inflate greatly. Thus, the more parameters one tries to ascertain with the inversion, the greater will be the variance of any parameter estimates. In general, this trade-off between degrees of freedom in the model and accuracy of the interpretation is arbitrarily controlled by the interpreter, and any error estimates are not meaningful if taken out of context. The trade-off compromise is fundamental and we shall return to it later.

For inverse problems which are highly linear and where the vector of model parameters has a natural order so that it can be considered a digitized version of a continuous function (for example, conductivity as a function of depth); Backus and Gilbert (1967, 1968, 1970) have devised an analysis to organize and quantify the trade-off problem and show just what aspects of the model that the available data can define. It is discussed later in the context of underdetermined problems, but is too ramified to be re-

viewed in detail. It has been applied more in whole earth geophysics than in mineral exploration.

UNDERDETERMINED MODELS

INTRODUCTION

If the inverse problem is formulated with more parameters than data, then it is clear that many models may all fit the data adequately¹, since the number of variables exceeds the number of data. Since presenting an infinite number of models is neither feasible nor useful, alternatives to this have been pursued. Earlier work on underdetermined problems attempted to present a representative suite of acceptable models. Alternatively, one can present some special or distinguished model of interest, and perhaps some indication of how different from this a model may be and still fit the data.

The first approach is exemplified by the Monte Carlo method in which models are generated randomly and tested for acceptability. Although somewhat cumbersome, it can work well for overdetermined problems where the total range in parameter space of models acceptable to the data is bounded, and an envelope can be drawn around the set of acceptable models. In fact, mapping this envelope is usually the main objective. However, the acceptable range is often not bounded in underdetermined problems. The nature of the deviations allowed by the data depends, of course, on the intrinsic uniqueness of the problem, which in turn depends on the physical principle involved (for surface measurements, gravity is intrinsically non-unique (Kellogg) but 1-D magnetotellurics is unique). Without going into problem-specific detail, it is safe to say that the commonest type of ambiguity in models is in the form of spatial fine structure. For example, in fitting surface gravity measurements, density models can have arbitrarily large oscillations added to them as long as these have sufficiently short wavelength that they average to zero over the shortest length scales which practical measurements can resolve. In general, the size of a model deviation allowed by the data increases as the spatial wavelength of the deviation decreases, in a manner analogous to the Heisenberg uncertainty principle in quantum mechanics. This can make the "representative suite" approaches described above somewhat less useful, as the envelope of acceptable solutions depends strongly on how finely detailed the models are allowed to be, and this is the subject of Backus-Gilbert theory. As an alternative, recent developments

1. In the following, we assume this to be the case. However, it is also possible that no models can fit the data adequately, if the data and the model are somehow incompatible. Then, the only course of action is to alter the model concept. A common example of this difficulty is attempting to fit a layered earth model to data where there are strong effects from lateral variations in structure.

in inverse theory have concentrated more on the second approach, that of displaying specific special models for specific purposes.

The obvious question, when designing special models (to which the answer is less obvious), is "Special in what way?". A number of answers exist, each with a different purpose: for example, the most probable model; the model with the smallest deviation in some sense from some best *a priori* guess; the model with smoothest structure; the model with the smallest maximum deviation from a uniform model, or; the model with the "simplest" structure in some sense. Note that these choices are all based on optimizing or extremizing some property of the model, while constraining it to fit the data, and are referred to as extremal models.

MAXIMUM LIKELIHOOD MODELS

The most probable model (in the sense of a maximum likelihood estimate of the model parameters) seems, at first sight, a most sensible choice. In the absence of *a priori* information about probability distributions for model parameters, this translates to fitting the data as well as possible. To see this, assume that the data errors $e = y - A^T x$ have a Gaussian distribution with zero mean and standard deviation σ . The conditional probability density function of the set of data y , given that the true model is that given by x is

$$f(y|x) = \frac{1}{(2\pi\sigma^2)^{\frac{n}{2}}} \exp\left(-\frac{e^T e}{2\sigma^2}\right)$$

What we wish to maximize, however, is the likelihood of x , given y , which is the other way around. However, it is a textbook result relating conditional probabilities that

$$f(x|y) f_d(y) = f(y|x) f_x(x)$$

where f_x and f_d are the (here *a priori*) marginal probabilities of the parameters and data respectively. Thus the most likely x is obtained by maximizing $f(y|x) f_x(x)$ (since $f_d(y)$ is not a function of x). The simplest assumption one can make is that no x is preferred above any other (at least within the range of values likely to occur in the calculation), and that $f_x(x)$ is constant. The solution is obtained by maximizing the function $f(y|x)$ above with respect to the elements of x . This leads to the equations of the classic least squares fit, namely

$$(A^T A) \hat{x} = A^T y$$

Unfortunately, because the matrix A has fewer rows than columns in an underdetermined problem, the matrix $A^T A$ is rank deficient and not invertible. The equations therefore have an infinity of solutions which may be quite different from each other in cer-

tain respects, but all are equally probable in the sense of fitting the data equally well. It may be that these differences are not important for the interpretation problem at hand. As noted above, the differences may often consist of spatially fine structure which one never hoped to resolve in the first place with the data set provided. Nevertheless, choosing a unique "most probable model" is not normally possible in an underdetermined problem if no *a priori* preferences for certain models are allowed.

If, however, *a priori* information about model probabilities is available, then the maximum likelihood approach above will generally yield a unique result. As the simplest possible example of how this works, assume that one believes that model parameter values (i.e. differences from those of an *a priori* model) in excess of some value are very unlikely, and that one is willing to go further and assume that if all geological structure models in the real Earth (or any plausible fictional one!) that fit the data were assembled and inspected, their parameter values would have a Gaussian distribution with zero mean and standard deviation σ_x . The *a priori* model parameter marginal distribution f_x would then be

$$f_x(x) = \frac{1}{(2\pi\sigma_x^2)^{\frac{n}{2}}} \exp\left(-\frac{x^T x}{2\sigma_x^2}\right)$$

The corresponding conditional probability density for x given y is then proportional to

$$f(x|y) = \frac{1}{(2\pi\sigma_x^2)^{\frac{n}{2}} (2\pi\sigma^2)^{\frac{n}{2}}} \exp\left(-\frac{x^T x}{2\sigma_x^2} - \frac{e^T e}{2\sigma^2}\right)$$

where $e = y - Ax$ as before. Maximizing this with respect to the elements of x yields the equations

$$(A^T A + \frac{\sigma^2}{\sigma_x^2} I) x = A^T y$$

This is just what arose before in the damped least squares approach, except that α is now given a specific value in terms of expected data and parameter variances, and the solution is now recognized as a maximum likelihood solution. The correspondence, however, is accidental; had our expectations about the probabilities of the model parameters been in a form other than the very simple distribution used above (Gaussian, with equal variance for all model parameters), a more complex set of equations would have occurred. The theory of this approach in geophysics was pioneered (Franklin 1970; Jackson 1979) as the "Stochastic Inverse" and has been generalized (at least theoretically) by later authors (e.g. Tarantola and Valette 1982a, 1982b).

The simplest description of the method is that it deliberately biases the solution away from the best-fitting solution towards the *a priori* solution believed

to be most likely. That the resultant model no longer fits the data perfectly should not be considered disturbing, because the data have errors. Since attempts to fit the data perfectly, i.e. to fit these errors, often introduce chaotic (or oscillating) structure into the model because of the random nature of the errors, it is better for the solution to be a compromise between what the data and the *a priori* information suggest.

Although this method works in principle for any type of *a priori* probability distribution of models, practical solutions are not yet realizable for all the problems one might be interested in exploring. An obvious example is the case of gravity modeling in a continuous or finely gridded cellular model, where the lithologies are known or suspected, and our *a priori* probability distribution for densities is multimodal, peaking at each of the mean densities for the several lithologies. Following the above approach leads to a general nonlinear optimization problem; the equations to be solved are not all linear, unlike the case for a Gaussian distribution. Although algorithms exist for solving such problems (see Gill, Murray, and Wright (1981) for a comprehensive review), they may not be economically feasible for routine inversion of realistically large and detailed models.

SMOOTHEST MODELS

A realistic model can often be obtained by choosing to fit the data "reasonably well" (i.e. just touching the error bars, as suggested by Jackson (1976) in his "most squares" approach) while optimizing some other property of the model itself (e.g. smoothness). However, what would be the point of picking a smoothest model when it is obvious that the real Earth is under no obligation to behave this way? The answer is that smoothing acts to wipe out structure in the model; any structure that survives this smoothing, that exists still in the smoothest model that fits the data, *must* be real. Figure 19.10c, taken from Constable *et al.* (1987) shows how this works. The solid line shows the resistivity-depth relation inferred from a data set using a conventional iterative least squares method and starting from a much simpler layered model. This model fits the data perfectly well. In this model, sharp transitions occur at 100 m in depth, at 9 km, and again around 30 km. Are these necessary? In the dashed line plot of the smoothest model (in the sense of minimum mean square second derivative of resistivity with respect to depth), the shallow transition has been smoothed. In reality, it may be sharp, but it could also be gradational over a depth range of up to a kilometre. Any belief that it is sharper than this *must* be supported from other data or beliefs (e.g. that the shallow lithology does have discrete units with different conductivities). Finally, following the smooth curve down to 9 km, we see that there is *no* evidence for the confined conductive layer suggested there by the

solid curve. Solutions become smoother as one's estimate of data error size increases, as shown in Figure 19.10b.

A smooth model is a useful way of avoiding overinterpretation, but there can be dangers in such an approach. A lack of fine structure in a model when such structure exists in the real Earth (even though it is unresolvable by the geophysical data) can lead to systematic bias in the interpretation. VES interpretation is a clear case in point. Unresolvable fine structure constitutes an effective anisotropy. If it is present and unrecognized, the resolved structure will be interpreted as deeper than it is in the real Earth.

IDEAL BODIES

Other extremal approaches have been used in the literature. An example is "Ideal Body Theory" in gravity interpretation (Parker 1974, 1975). This method is intended to be applied to the fairly simple situation where the gravity anomaly can be attributed to a single body of all positive (or all negative) anomalous density in a uniform host medium. This situation can arise directly, or after subtracting from the measured anomaly the effects of all other (known) anomalous densities. The object is to select out of all anomalous bodies that fit the data, that one which has, anywhere in the body, the smallest peak density contrast with the host. In other words, it is to find the least upper bound on the anomalous density. One then knows for sure that the real body must have an anomalous density contrast which exceeds this value somewhere, and the information may be decisive in deciding against a candidate lithology which is known never to be this dense. It turns out that the resulting "ideal body" is always uniform in anomalous density, and its shape may not resemble that of the real body at all. Resemblance of shape, however, is not the goal of this extremal method.

The situation can be turned on its head. If the maximum density contrast of the body is assumed known on other grounds, one can then see how deep one can push the top of a causative body limited to this density contrast and still produce an anomaly which is large enough to fit the data within the error bars. This then gives an upper bound on the depth to the top of the body. Again, the shape resemblance of the extremal body to the real body may be poor. Ander and Huestis (1987) give a good example of the method applied to gravity interpretation.

The method can be extended to use both gravity and magnetic data simultaneously. As an example, Chavez *et al.* (1987) used both gravity and magnetic data for a cylindrically symmetrical model of the Darnley Bay anomalous feature in northern Canada, which was thought to be a dense intrusion. Figure 19.11 shows the resulting anomalous-density/depth-to-top and magnetization/depth-to-top trade-off

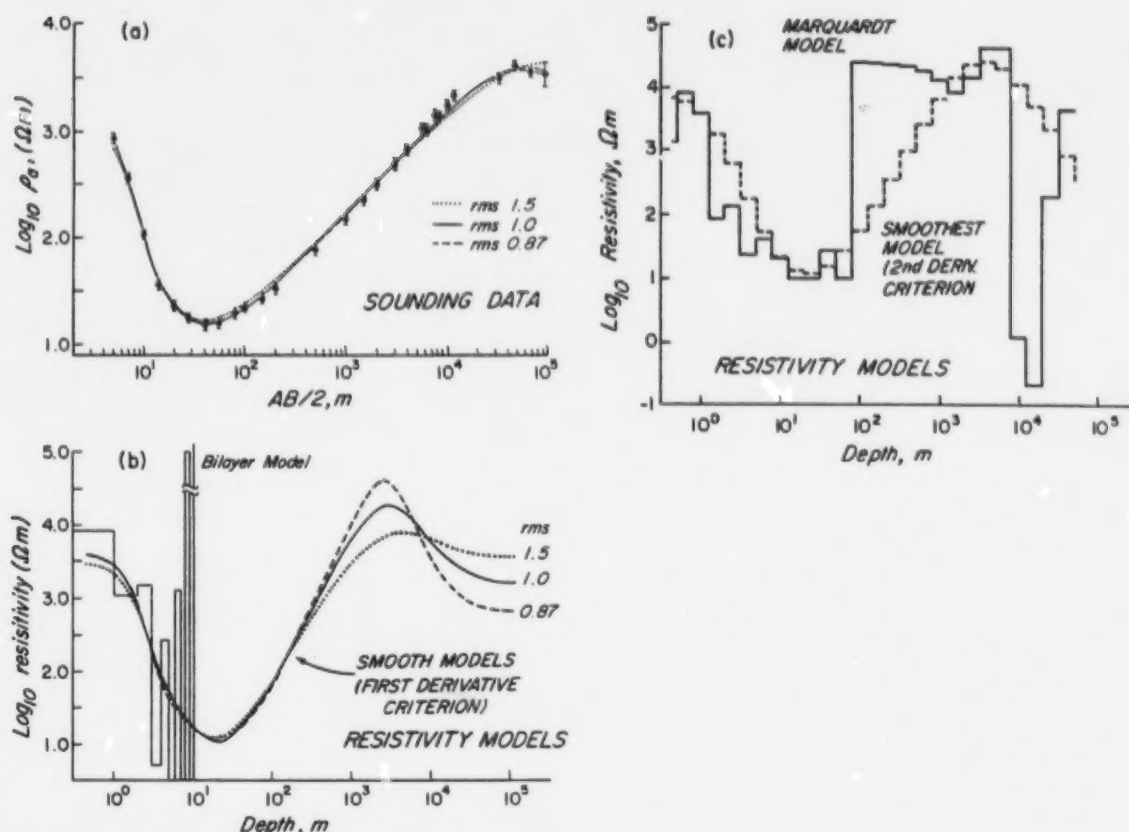


Figure 19.10. Examples of extremal inversion of a VES survey where measures of smoothness are maximized under the constraint that the model data fit the observations to a given accuracy (from Constable et al. 1987): a) shows the VES sounding data points and the fit achieved by the smooth models shown in b); b) shows three earth models which each were required to fit the data to the RMS error shown on the curves, and also to maximize a first derivative measure of smoothness. The oscillatory curve is a model computed using Parker's (1984) bilayer algorithm which fits the observations more exactly than the smooth models. It involves unrealistically large and small resistivities and is a theoretical curiosity rather than a practical solution. However it shows the danger of using best fit as the only criterion for optimization. The extreme oscillations act like a very strong anisotropy and cause the model to have a very contracted depth scale. c) This shows a model obtained with a Marquardt, damped least squares algorithm. The model was parameterized with 27 fixed layer thicknesses in which the resistivity was unknown. The starting model was from an earlier solution for six layers, and the strong boundaries of the starting model remain in the final solution. Also shown is an extremal model employing a second derivative measure of smoothness. It is clear that only the main structure in the model is required by the data to be present, and there is no need for the low resistivities interpreted at depths below 10 km to be succeeded by high resistivity.

curves. All solutions fitting the gravity and magnetic data within the estimated errors *must* lie above the curves. Clearly the density must exceed 3.0 g/cc even if the body outcrops (the reference density being 2.7 g/cc). The causative body does not outcrop, and is probably in the basement. Since between 1.2 and 2.2 km of Proterozoic and Paleozoic sediments overlie the basement, a belief that the body lies in the basement forces the density to lie between 3.1 and 3.4 g/cc, implying an ultrabasic rock rather than a gabbro as a candidate intrusion. This is an example of a conclusion which does not rely in any way on actually finding the probable shape of the intrusive body.

Other Extremal Models

Gravity interpretation also affords examples of other extremal methods. Extremal methods which find the smoothest density model that can fit the data are not very appropriate if one knows that the real Earth has fairly distinct lithologic units with fairly well defined densities. Put another way, how does one incorporate this rather vague *a priori* preference for a certain style of density variations without forcing them explicitly by using an overdetermined model with only a few discrete units? Last and Kubik (1983) and Guillen and Menichetti (1984), for example, have shown how to compute the "most compact"

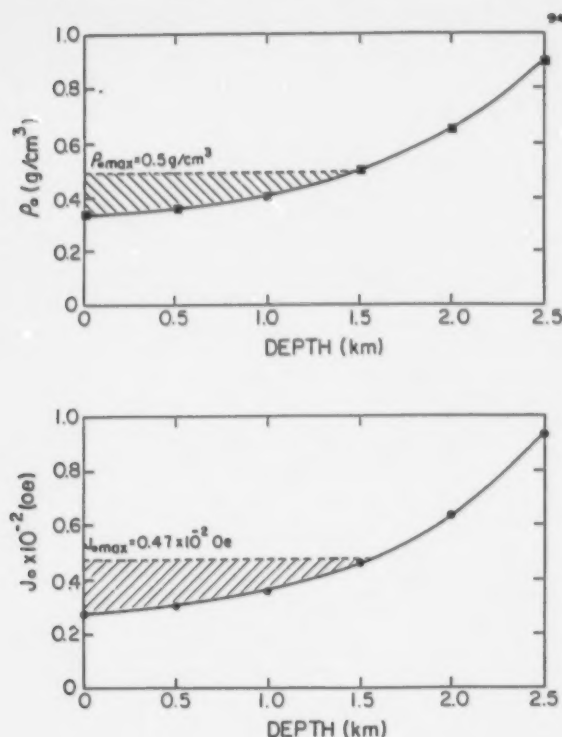


Figure 19.11. Least upper bounds on anomalous density (top) and intensity of magnetization (bottom) versus depth to the top of the anomalous body which gives rise to the Darnley Bay magnetic and gravity anomaly, taken from Chavez et al. (1987). The dashed lines on each plot represent the authors' estimates of a priori reasonable upper limits on these parameters; the ranges of feasible solutions are the shaded regions.

body that fits a given anomaly. This prevents the extreme "smearing" of density contrasts that occurs in smoothest models, but has its disadvantages too. To the extent that the data do not constrain it (because, for example, of large error bars), the modeled body will always attempt to shrink to a point mass of infinite density, unless suitably restrained. In a similar vein, Mottl and Mottlova (1972) have described methods for finding a body which fits the data and which is also most like some specified shape (as defined by its moments).

Bailey and Reford (1987) have adapted a method which has fruitfully been applied to one-dimensional models in seismic reflection inversion (Levy and Fullagar 1981) to the two-dimensional gravity modeling problem, in which a "simplest" model is found fitting the data. Simplicity is here defined as minimization of the mean absolute value of the density gradient. This optimization principle does not "object" to sharp density transitions more than to smooth gradational transitions, but it does "object" to oscillating or overshooting transitions.

This prevents the occurrence of unnecessary large and unrealistic density excursions whose effects on the measured anomaly are cancelled by immediately adjacent and equally unrealistic density excursions of the opposite sign. It acts as if smoothing operated on oscillatory transitions but not on monotonic transitions, and thus it does more or less what an interpreter would try to do in coping with the excesses of a simple iterative unconstrained fit to the data.

Like many of the extremal methods, the resultant model may in fact be too extreme (here "simple") compared to the real Earth. However, it is very straightforward in this type of modeling to incorporate any known density information obtained by surface or borehole sampling. The model is generally represented as a grid of small cells of uniform density, in some of which the density may be constrained to specified values, while the other densities are varied to perform the optimization. Figure 19.12b shows a simple example of a dipping dike modeled by a grid of cells, and Figure 19.12a the associated gravity anomaly. Application of the simplicity optimization to this data yields the unrealistic, and very gradational, density model shown in Figure 19.12c. If the densities along the surface are constrained to their true values, as if geological sampling had been done, the "simplest" model, shown in Figure 19.12d turns out to be very similar to the true model.

ERROR APPRAISAL

Some extremal methods are directed at trying to model the body itself by incorporating additional expectations about the nature of acceptable models into the modeling process. Others (e.g. ideal body theory) attempt to answer a global question about all bodies that fit the data (e.g. what is the maximum depth-to-top we need believe?). The question of what are the errors in the model does not arise in the second type, because the model actually found is not intended to be true, only extremal. However, in the first type of extremal model, we hope that the property we have chosen to extremize is one that (in a probabilistic sense) the Earth does also. We must remember that we may be wrong, and it is often necessary to have some idea of how far the real Earth may deviate from our special extremal model and still fit the data acceptably.

For error estimation, the previously mentioned linear model error appraisal methods developed by Backus and Gilbert (1967, 1968, 1970), which recognize the problems of resolution mentioned above, are particularly suitable. In many problems, all models that fit the data will look identical if smoothed heavily enough. There is a trade-off between the error of the model property, and the spatial resolution with which that value is estimated. It is disappointing to realize that there is no one answer to the question about the size of the error bars at a given point in a model. The answer depends on the spatial resolution of the smoothing one is willing to accept. However,

The test anomaly.

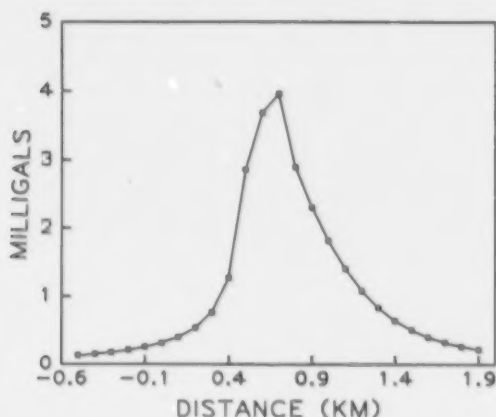
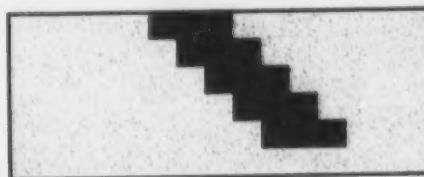


Figure 19.12. Examples of two-dimensional gravity modeling using a simplicity extremal condition. The test data are from a dipping dike model of uniform density, and the inversion model is a cellular structure with unknown density in each cell: a) shows the test gravity anomaly; b) shows the dike-like test structure; c) is an inversion of this anomaly using only the simplicity extremal criterion and the data fitting constraints. The result is a smeared density structure at depth (which creates the anomaly flanks) and a local, in which is imbedded a compact variable density structure near the surface (which creates the anomaly peak) - not a very satisfactory result, all in all. d) This shows how addition of a constraint on surface densities leads the solution to a very much better result (from Reford and Bailey 1987).

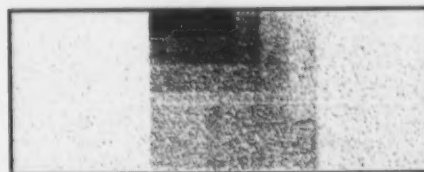
The target model used to generate the data and to start the iteration.

$S = 0.1050$



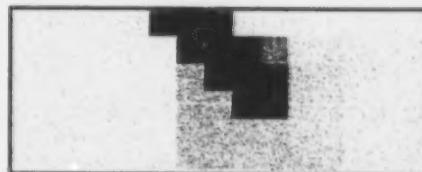
Minimum S model with no constraints.

$S = 0.0479$



Minimum S model with surface densities constrained to true values.

$S = 0.0754$



DENSITY SCALE

Density range +0.7 to -0.1 gm/cc

the trade-off between error and resolution can be plotted for any desired representative points in the model as "trade-off curves", and a quantitative picture of the spatial resolution achieved in various regions of the model can be computed for a given error level.

JOINT INVERSION

Often, the ambiguities inherent in a given type of data are complementary to those in another type of data. This has led to the concept of "joint inversion" of several data types at once. Figure 19.13 taken from the paper on smooth modeling by Constable *et al.* (1987) shows the data and results of inverting both magnetotelluric and Schlumberger resistivity data for a given site, in isolation from each other, and together. The resistivity method is best at detecting resistive excursions from the mean resistivity, and the magnetotelluric method is insensitive

to these, but has deeper penetration. It can be seen how joint inversion has incorporated the best features of both and still managed to fit the data.

IMAGING METHODS

The philosophy of the interpretation methods described so far has much in common with that of statistical hypothesis testing. One tries to formulate useful questions quantitatively, and have the data answer them. From the answers, one tries to build up a picture of (some aspects of) earth structure. The questions posed, and the sequence in which they are asked, are usually dependent on the features seen in the survey data. However, the objective of much exploration geophysical surveying is to create directly some kind of image of earth structure in map or sectional form. The geophysical survey and data interpretation will be designed specifically to achieve this end. However, this approach can only be used when

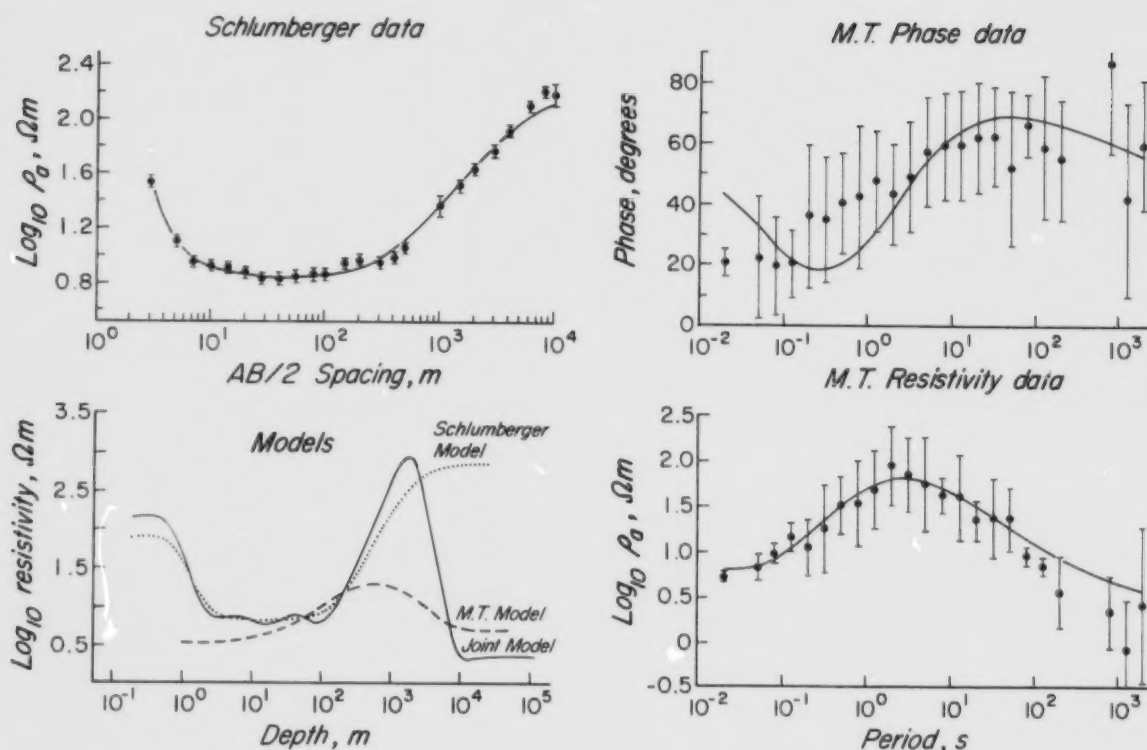


Figure 19.13. Showing the importance of bringing as much information as possible to bear when doing an inversion. Separate and joint solutions for a layered resistivity structure from VES and magnetotelluric survey data are obtained using the smoothest model extremal method. Solutions from separate inversions do not agree well with each other. However, it turns out that both sets of data are indeed compatible with a common model (from Constable et al. 1987).

the type of geology and the character of its geophysical response, is reasonably predictable, so the survey can be tuned to the task.

For imaging, one wants a method of data analysis that can be applied more or less routinely to the whole survey. A paradigm in this regard is the seismic reflection method. The data analysis is a series of manipulations that leads directly to a geologically understandable image, without employing a model fitting process where values are found for unknown parameters. But, being a method based on non-dispersive wave propagation, reflection seismology enjoys certain advantages. There is much greater resolution and less ambiguity in the interpretation process than for methods based on potential or diffusive fields.

Despite the greater fundamental difficulties, survey and interpretation procedures can sometimes be devised for the common geophysical methods of mineral exploration which can directly provide an image as output. The results will, naturally, not provide the detail of a wave reflection method, but otherwise the approach is similar. An elementary example in magnetic mapping is the apparent susceptibility mapping method, where, to the extent that rock

formations in the survey area are inductively magnetized and the geological contacts are steeply dipping, a well-made aeromagnetic map can be directly turned into a limited resolution map of magnetic susceptibility in the near-surface rocks. Limited resolution here implies that a lateral spatial average value of susceptibility is found, with the extent of lateral averaging determined by the flight height and the line spacing of the survey.

Implicit in imaging is a one-to-one correspondence between data sets and images. It is a return to solving the evenly determined problem. It is still based on a conceptual earth model, one which (hopefully) is applicable to all the survey area. The parameters of the model are spatial functions that can be presented in image form. As in the method of characteristic measures, the directly observed data are manipulated to estimate intermediate data quantities from which the local values of the model parameters can be computed algorithmically. Parameterization of the model and selection of the intermediate data are carefully done in advance, in order to make the inversion from intermediate data to model parameters as independent as possible of the data itself. Ideally, it would be a linear transform-

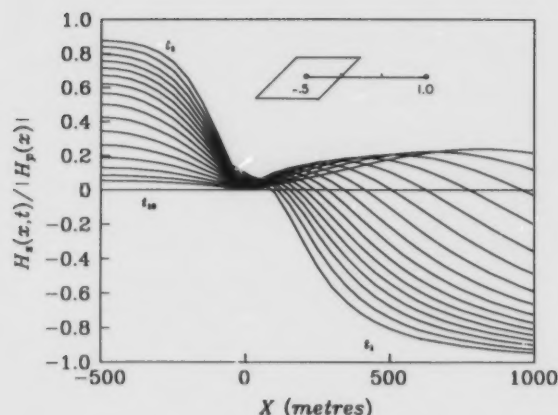


Figure 19.14. The fixed transmitter-moving vertical component receiver, UTEM step response of a layered earth model. The response is plotted as a fraction of the free space primary field. Overlapping profiles of this form are the basic data of the ML depth imaging inversion method.

mation of some kind. Ambiguities inherent in the geophysical method are handled by the design of the imaging procedure. The quantities to be imaged, and the information about them which is inherent in the survey data, must be carefully balanced against each other, so that the inversion step is essentially an evenly determined problem. The number of observational data in the original survey will generally much exceed the number of parameters in the image; but the reduction to intermediate data will use this to perform some kind of averaging that reduces not only the effects of data error, but also those of local model misfit.

As an example of imaging in cross-sectional form, a relatively new approach to the interpretation of EM sounding surveys which has been devised by Lamontagne Geophysics and Macnae and Lamontagne (1987) is reviewed. The illustrations in Figures 19.14 through 19.18 are from Polzer (1985) who investigated the relationship between the Macnae/Lamontagne imaging method and geophysical inverse theory. The objective is an electrical conductivity cross-section of the Earth along a survey profile. The survey consists of wide band, time-domain, EM measurements made by the fixed transmitter-moving receiver method along segments of the survey profile; segments which overlap each other in somewhat the same manner as multifold seismic reflection profiling or dipole-dipole resistivity/IP profiling at multiple n spacings. The method is designed for investigating geology that has a stratified aspect; one where the conductivity section has a structure which varies more gradually (or at least in a less complicated fashion) laterally, than vertically. Thus, an earth model which locally is horizontally stratified is an appropriate basis for the inversion.

Figure 19.14 shows the survey configuration and the form of the field observation on a segment of the profile measured from one transmitter loop. The data shown are synthetic, for a horizontally layered model, and they are vertical component measurements of I to H step response (The response of $H_z(t)$ to a step in transmitter current $I(t)$) such as are provided by the UTEM system. Because the field amplitude drops rapidly with distance from the transmitter loop, the data are shown in a normalized form divided by the free space primary field (which is also vertical). The complete data at any point on the profile consist usually of an in-loop measurement and a pair of measurements with transmitter loops on either side. But, we first consider how data from a single transmitter can be inverted.

The key to the method is noting that all stratified earths have a response that looks qualitatively like Figure 19.14, in that a very similar transition from a predictable negative inductive limit response (-200 percent) at early time to a vanishing positive overshoot response at late time. Then instead of considering the model fitting to be an exercise in adjusting the modeled field amplitudes to the data amplitudes, it is considered as fitting in delay time (Figure 19.15).

In revised form, the data at any one observation point may be described as measurements of relative delay time; the time at which the observed field reached a given point in its response transition relative to the response at corresponding time for a reference model. This data form has two great advantages: it is nearly independent of the distance between the transmitter loop and the receiver, as is shown in Figure 19.16, and also there is a nearly linear relationship between it and the vertical conductivity structure. The first point means that data from different transmitter positions and receiver points may be averaged together to obtain a best (compromise) estimate of response, and from it obtain the layer structure at a given point on the survey profile. The second makes the inverse process direct. To a good approximation, the result is independent of the whatever reference model was used in making the relative time measurement. The depth resolution of the conductivity model is also predictable. A slightly overdamped estimate of $\sigma(\ln z)$ is obtained with depth resolution more or less constant in $\ln z$ between an upper and lower limit which is determined by the survey characteristics and the ground structure. Some synthetic test examples are shown in Figure 19.17. The inversion can be iterated, as is shown in the tests, but only minor improvements are obtained. A field example of the image constructed from a short multifold profile in southern Ontario is shown in Figure 19.18. A known local change in the character of a resistive bed at 800 m depth is seen despite the limited extent and relatively great depth of the feature.

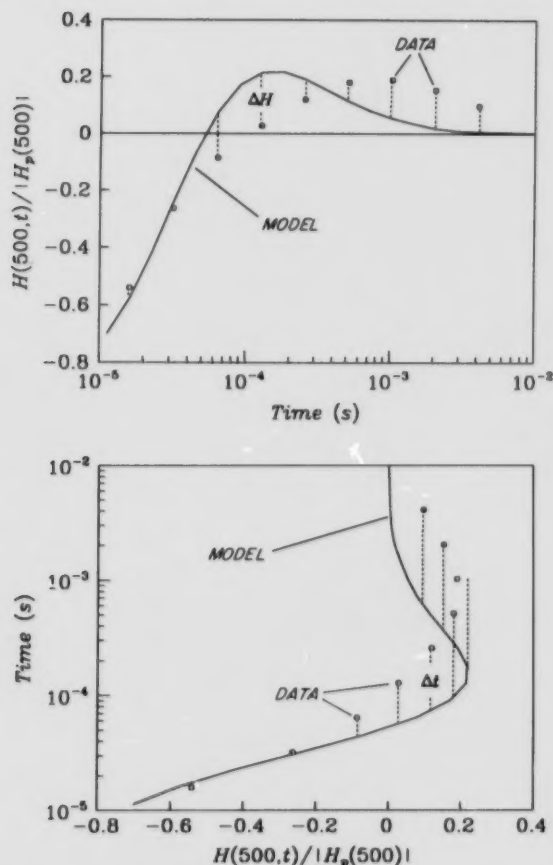


Figure 19.15. The key feature of the ML technique is consideration of the inverse problem as a fitting problem in delay time (top) instead of field intensity (bottom). The field data at each station are recast as measurements of relative delay, i.e. observed delay time ratioed to the corresponding delay time in a simple reference model like a half space or a shallow thin sheet. If vertical and horizontal component measurements are both available, they can be combined at this point to give a better estimate of the relative delay.

Imaging is a frontier area for geophysical development. In general, imaging methods are not just special data analysis techniques that can be applied to standard geophysical survey data. The survey and the data analysis method will usually need to be designed as a unit in order to achieve the imaging objectives optimally. It is essential that all gross ambiguity problems be resolved in advance (usually by *a priori* assumptions) and that an optimum balance be struck between information content in the data and degrees of freedom in the earth model. Only if this balance is achieved, will the imaged information be a maximally resolved, but also a stable estimate of earth structure.

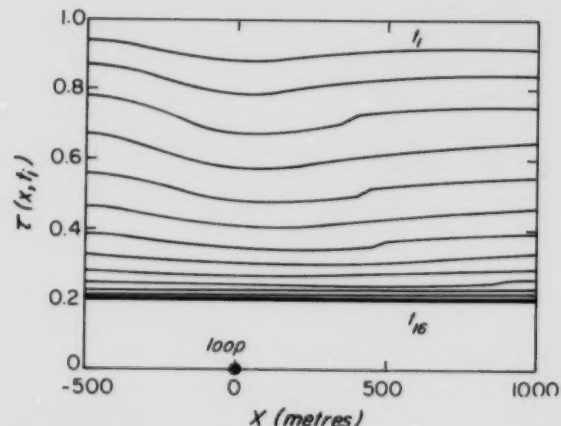


Figure 19.16. Relative time measurements for a model of a conductive layer over a more resistive half space on a line out from the centre of the transmitter loop. The reference model is a uniform half space. Relative time asymptotes to unity at early (reference) time and to 0.2 at late time, corresponding to the ratio of conductivities in the test and reference models at surface and at depth. There is very little variation with station location, making it possible to combine data from different receiver stations and transmitter locations into a single estimate of relative time for each part of the survey profile.

FUTURE DEVELOPMENTS

Inverse methods have had a significant influence on how interpretation of exploration data is thought about. It is probably fair to say that the flowering of inverse methods that was stimulated by the arrival of large computers during the 1960s has, in fact, outstripped the development of practical computing hardware and software for the moment. Many very sophisticated imaging, extremal, and robust modeling algorithms have already reached the stage of appearing in textbooks on the subject. Nevertheless, many of these have had only research use, and are still not convenient or economic propositions on large models in two or three dimensions, at least for routine use. Over the next decade we can therefore look forward to significant advances in the application of inverse theory to exploration resulting from development of computing power alone.

ACKNOWLEDGMENTS

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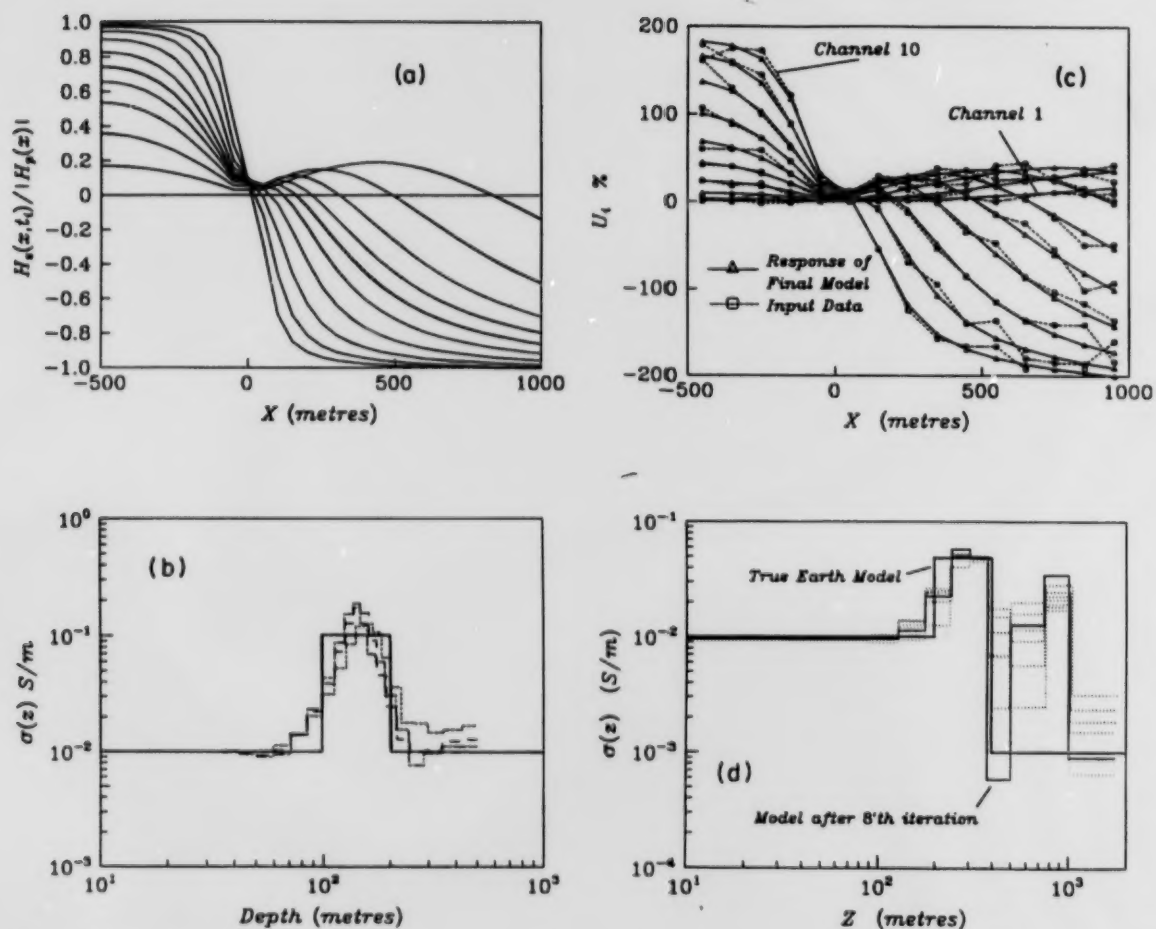


Figure 19.17. Tests of the inversion of relative time (as a function of reference time) to conductivity (as a function of depth). The ability of the resulting earth model to fit the original observational data is also shown. In a), error-free data are converted to relative time and inverted using a half space as the starting reference model. The solution is iterated twice to see if an improvement is obtained. The result is a smoothed version of the test model which is not much improved by iteration. b) Shows that the original observations are fit almost perfectly by the resulting model. The consequence of substantial error in the data is tested in c). The inversion has difficulty in seeing a resistive substratum under a thick conductive layer but otherwise is good. d) Shows that the resulting model fits the original data well. As in a), iteration is not helpful. The relationship between the relative time data and the model data is sufficiently linear that the choice of reference model is unimportant in relation to the fundamental ambiguities of the inversion.

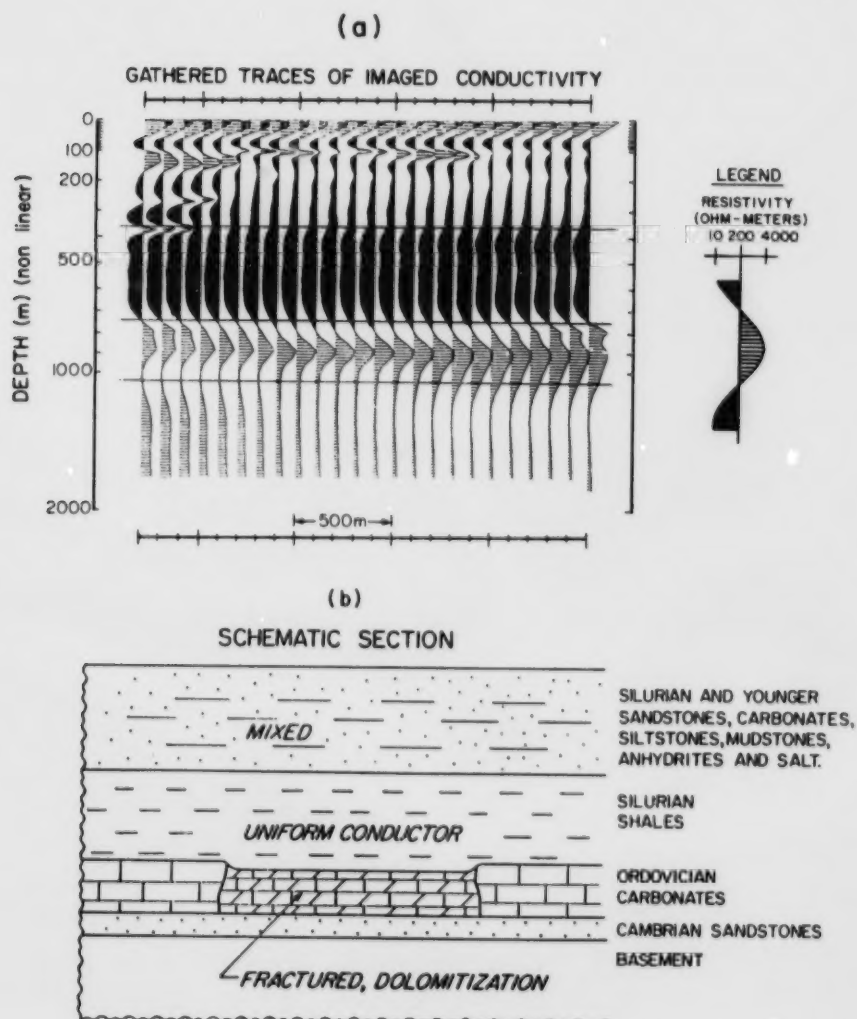


Figure 19.18. A practical example of ML conductivity depth imaging from a survey over a Paleozoic sedimentary section in southern Ontario. Note that a nonlinear depth scale is used in this presentation. A resistive stratum is encountered at about 800 m which is a little deeper and/or less resistive in the middle of the profile than on either side. The known geological structure is shown schematically with the anomaly in the resistive stratum corresponding to a known zone of fracturing and dolomitization.

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20. Remote Sensing for Surface Mineralogy

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ABSTRACT

In marked contrast to the industry-based demand-pull for exploration geophysics technology, early remote sensing techniques developed in response to a government research-push.

Consequently, it is only recently that advanced sensors and data interpretation techniques optimised for mineral exploration have begun to appear.

These new systems are starting to provide species identification and mapping for minerals in the silicate, carbonate, and iron oxide groups. Although the general purpose remote sensing systems, such as Landsat MSS and SPOT, will always be important in structural studies, it is clear that this new generation of sensors will be of great utility for mineral exploration in areas where rock or residual soil is exposed.

Research with high-sensitivity spectrometer systems, both in the field and from low altitude aircraft, has shown that the characteristic mineral reflectance features, known from laboratory studies, can be detected in spite of interference from the atmospheric, weathering, and vegetation effects. The nature of this interference can be understood in terms of simple mixing models which, in turn, have led to the development of image enhancement techniques to remove these unwanted effects.

The demonstrated ability of short-wave infrared scanner systems to map hydrothermal and epithermal alteration systems is perhaps the most important current application of this new technology.

The paper will review several case studies of this type and will discuss the results from more detailed airborne spectrometer surveys where detailed mineral identification has been possible.

INTRODUCTION

The recent history of remote sensing for mineral exploration is notable because almost all the imagery was collected by systems designed for monitoring renewable resources. The sensors, developed as part of a government push for space technology, were rarely optimized for mineral exploration applications. Although a considerable number of remote sensing systems have been specifically built for mineral mapping, most have been used to study the geology of planets other than the earth. It is an unfortunate fact that the exploration industry has not been seen as an important client by the government space agencies or the space industry lobby.

Despite this lack of interest, the industry has been among the most successful users of remote sensing. The Landsat program, perhaps the most striking example in this regard, has been both a stimulus and a hindrance to geological remote sensing. It introduced remote sensing and digital image processing to a wide variety of users but, most importantly, it opened a new dimension to structural geology by providing a uniform, synoptic view of the earth at a scale previously unavailable (Hodgson *et al.* 1974). Landsats' undoubted success in this latter role has, to some extent, masked the damage it has done to the cause of mineral mapping using the spectral reflectance properties of the surface.

Because the Landsat MSS is a vegetation-mapping sensor, operating in that region of the electromagnetic spectrum where there is the least mineralogical information, many geologists dismissed remote sensing as a tool for mineral mapping.

Happily, the situation is improving. Sensors are now being designed with mineral exploration in mind. Mid-infrared systems, first proposed to map the mineralogy of the moon (Lyon 1964), are starting to provide mapping of primary silicate mineralogy, while short-wave infrared systems, sensitive to hydroxyl-bearing minerals are showing great potential for the mapping of alteration and metamorphic minerals. The visible-near infrared region, so long dominated by the Landsat MSS, is also being revisited with new systems specifically tuned to discriminate the various iron oxides.

These systems and their potential for mineral exploration are the subject of this paper. In taking this narrow focus on mineral mapping we do not imply that this is the only important application of remote sensing in mineral exploration. The use of classical photogeological methods will always be of the utmost importance, and there is an emerging area of geobotanical remote sensing that may have important application in densely vegetated areas. For a more general coverage of geological remote sensing the reader is referred to a number of excellent reviews and books on the subject (e.g. Goetz and Rowan 1981; Siegal and Gillespie 1980).

We address the following questions:

1. What is the potential information about surface mineralogy that could be obtained by remote sensing?
2. How is this information degraded by the effects of sensor limitations, atmospheric attenuation, weathering processes, and vegetation cover?

3. To what extent can the above degradations be compensated by suitable data processing?
4. What use is this mineralogical information once it has been obtained?

THE BASIC INFORMATION

All sensor systems, both remote sensing and geophysical, measure the spatial distribution of some physical property. If these systems are to be useful, two criteria must be met:

1. The variability of the physical property must be associated with the features we are seeking to map.
2. The physical property must be of sufficient contrast to be seen above the noise of the sensor system.

Whereas density, magnetic susceptibility, or conductivity are the physical properties measured by geophysical systems, the wavelength dependence of reflectance is the critical property measured by remote sensing systems.

In order to satisfy criterion 1 above we must establish that minerals can be discriminated by reflectance measurements in the three main atmospheric windows currently available for remote sensing. These windows are the visible-near infrared (VNIR) 0.4 to 1.1 μm , the short-wave infrared (SWIR) 1.1 to 2.5 μm , and the mid-infrared (MIR) 8 to 14 μm .

Laboratory measurements of pure minerals are extensive and detailed. VNIR and SWIR mineral reflectance measurements by Hunt and Salisbury (1970, 1971a, 1971b, 1971c, 1972, 1973a, 1973b, 1973c, 1974a, 1976a, 1976b) provide an excellent starting point and these are now being supplemented and refined by other workers (Krohn 1986; Crowley 1984; Gaffey 1985). Of the wide range of minerals measured in the work above, only a few commonly occur at the surface, and we shall restrict our attention to these.

The spectra (colours) of minerals in the VNIR are, to a large extent, determined by their transition and rare earth element concentrations (Hunt 1977). Because iron, in the ferric and sometimes the ferrous state, is usually the only element in sufficient abundance at the surface to affect the spectrum, its presence or absence usually determines the VNIR spectrum (i.e. most rocks and soils are either reddish or grayish!).

Figure 20.1 shows the spectra of the major iron oxides. They are characterized by very low reflectance (strong absorption) around 0.4 μm , a reflectance maximum at 0.65 μm (red), and a weaker absorption around 0.95 μm . There are clear differences in the spectra of the different oxides, indicating that remote sensing techniques could distinguish and map them.

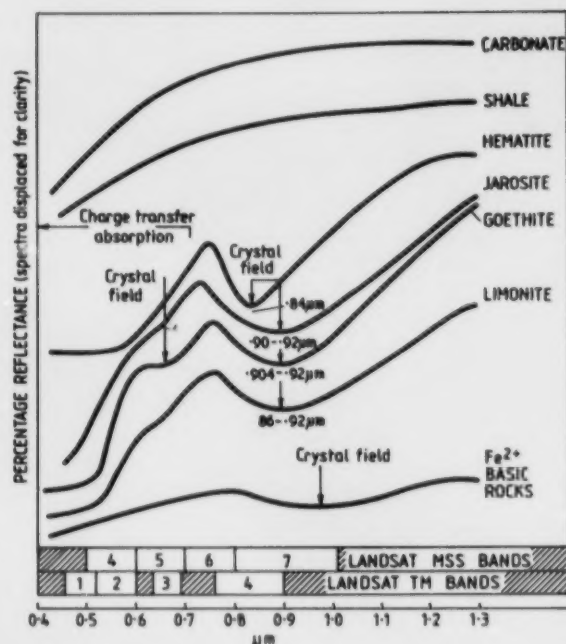


Figure 20.1. Reflectance spectra of the major iron oxide minerals in the VNIR portion of the electromagnetic spectrum.

In exceptional circumstances a few other minerals can be detected remotely using VNIR techniques. Rare earths have very characteristic spectra (Rowan *et al.* 1986) while very high-grade nickel mineralization might be recognizable because of its characteristic green response.

Given the restricted amount of mineralogical information and the broad-band, non-optimized nature of the available sensors, it is perhaps surprising that VNIR remote sensing has performed as well as it has for geological mapping.

In the SWIR region, much more mineral discrimination is possible. Here, combination and overtone vibrational transitions of hydroxyl and carbonate groups produce sharp, diagnostic absorption features in the reflectance spectra. Some of these features are obscured by water absorption but enough remain within atmospheric windows, to enable most of the phyllosilicate, amphibole, and carbonate minerals to be discriminated (Hunt 1979).

Figure 20.2 shows the reflectance spectra for some hydroxyl and carbonate minerals. The most important characteristics are the positions of the strong absorption features between 2.17 μm and 2.35 μm . Minerals with Al-OH groups tend to absorb near 2.2 μm while those with Mg-OH groups have features near 2.35 μm . The less common Fe-OH groups are intermediate, usually near 2.28 μm .

The MIR region absorption spectra of minerals have been extensively studied (Farmer 1974; Karr

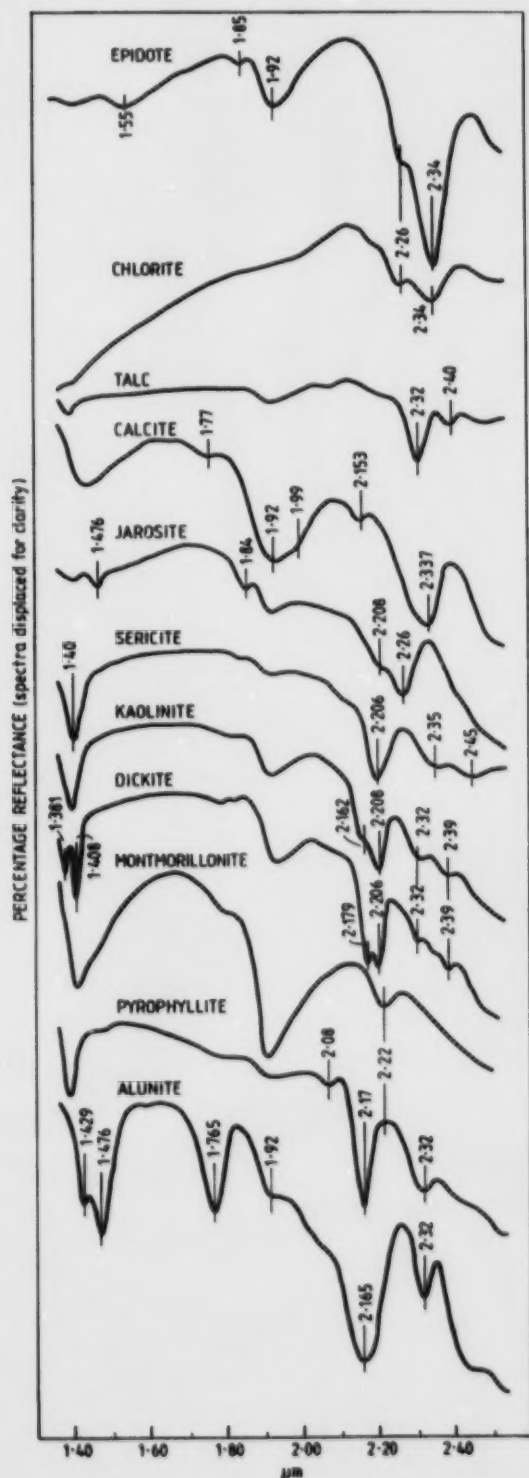


Figure 20.2. Reflectance spectra of selected minerals on the SWIR part of the electromagnetic spectrum.

1975) but, although these spectra can provide a useful guide to mineral reflectance (or emittance), they are insufficient. Until recently, the available compilations of MIR reflectance spectra were based on results from the 1960s by Lyon (1964) and Hunt and Salisbury (1974b). However, the FTIR work of Salisbury *et al.* (1987) has considerably alleviated this problem.

The MIR atmospheric window (8 to 12 μm) is currently the only region where the primary silicate mineralogy can be determined. Here, the reflectance properties of minerals are more complex than at shorter wavelengths because the relative intensities, and even the apparent wavelength position of spectroscopic features, are grain-size dependent (Salisbury *et al.* 1987). However, the most important feature, a strong reflectance maximum associated with the stretching motion of Si-O bonds, is diagnostic of the felsic content of the silicates. The more mafic a rock, the longer is the wavelength of the reflectance maximum (Logan *et al.* 1973). Figure 20.3 shows the reflectance spectra for selected silicates.

In addition to the grain size complications mentioned above, the MIR region is currently observable only by sensing emitted radiation. This complicates the interpretation process as the surface temperature is now an additional unknown in the measurement. In a review such as this, it is not feasible to encompass mineral mapping in both the reflected and emitted parts of the spectrum. As a result, the MIR region will not be treated further. However, the signal processing and data interpretation considerations are similar to those discussed for the reflective regions of the electromagnetic spectrum. Kahle (1987) and Kahle and Abbott (1986) provide an excellent introduction to the state of the art in MIR multispectral remote sensing.

Figures 20.1 to 20.3 indicate that reflectance spectroscopy can provide considerable mineralogical information. The question that remains is, "How much signal, relating to lithology and mineralogy at depth, is available to a remote sensing system?" Because these sensors see only the properties of the top few microns of whatever is exposed at the surface, primary mineralogical information is generally badly degraded by weathering and surface cover (usually vegetation).

The effects of weathering can be understood by studying the spectra of surface samples of rocks and soils while the problem of vegetative cover can be solved, to some extent, by suitable image processing techniques.

REFLECTANCE SPECTRA OF ROCKS AND SOILS

Finding adequate outcrop is perhaps the most vexing problem for much field geology, and it is nonetheless so for remote sensing. Clearly these systems rarely

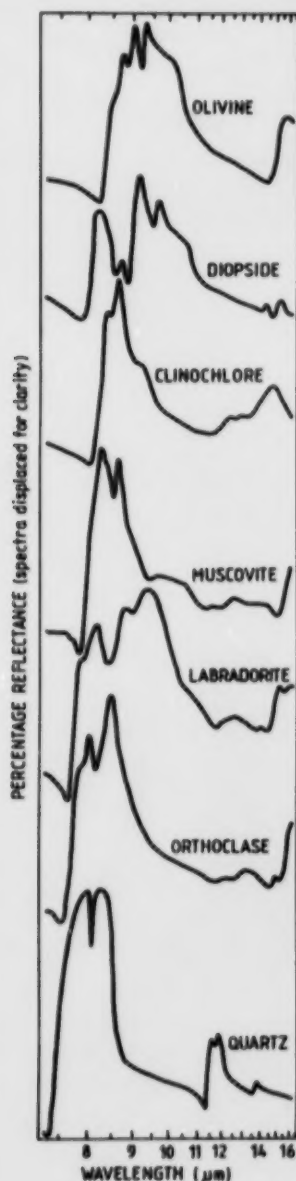


Figure 20.3. Reflectance spectra of selected silicates on the MIR portion of the electromagnetic spectrum.

see primary mineralogy, hence, if the results are to be interpreted correctly, consideration of the local geomorphology is critical. Once we have established whether the soils are residual or transported, their mineralogy can be understood correctly.

The chemical breakdown of primary mineralogy by weathering is illustrated (and greatly simplified) in Figure 20.4. This process of increasing hydration and cation leaching will, if allowed to continue, result in little more than iron oxides, kaolinite, and

quartz left at the surface (Butt 1981). By coincidence, these are the very minerals best detected by remote sensing systems, iron oxides in the VNIR, clays in the SWIR, and quartz in the MIR.

However, although good mapping of the products of prolonged chemical leaching may be of interest to geomorphologists and pedologists, there is little information left for geologists about the lithology at depth. Given that the primary mineralogy is rarely exposed, remote sensing will make the greatest contribution in areas of slight weathering (see Figure 20.4). These areas will be exposed either where there has been little regional weathering (e.g. the western USA), or where a deeply weathered profile has been dissected back to near fresh rock (e.g. parts of Australia).

In this slightly weathered zone most of the three-dimensional silicates other than quartz are usually badly altered but the pre-existing phyllosilicates, carbonates, and sulphates tend to remain unaltered. These latter minerals are often themselves the product of some earlier hydrothermal or metamorphic alteration process and which can be of great interest for exploration. Here then, is a major role for remote sensing: the location of increased concentrations of alteration minerals and the characterization of these mineral assemblages.

As we move from slightly weathered zones into areas of increased weathering intensity, it becomes much more difficult to distinguish alteration zones from an increasingly clay-rich background. This problem provides the most serious limit to the application of remote sensing to alteration mapping in deeply weathered terrain such as the Yilgarn of Western Australia.

The spectra of rocks and soils are the spectra of mineral mixtures and, to a first approximation, are often considered to be linear combinations of the component mineral spectra. However, the extent to which this approximation holds is a complex function of the crystallinity of the sample and the particular minerals themselves (Clark and Roush 1984).

SWIR spectra of surface rock samples usually show the presence of only one mineral, either the dominant primary phyllosilicate or some clay resulting from weathering. Less often, two minerals can be identified and, on rare occasions, three. Spectra of soils almost always show only the dominant mineralogy.

Reflectance measurements, either in the field or on samples brought back to the office, can provide a rapid, powerful method for mapping alteration minerals difficult to recognize in hand specimens.

Figure 20.5 shows the simplified geology of the Anastasia prospect in northeastern Queensland. A series of quartz-clay-pyrite altered volcanic vent breccias (Vb) are set in a northeast-trending belt of flow-banded rhyolite (Av). To the north, the McDevitt metamorphics (Pm) host narrow, linear,

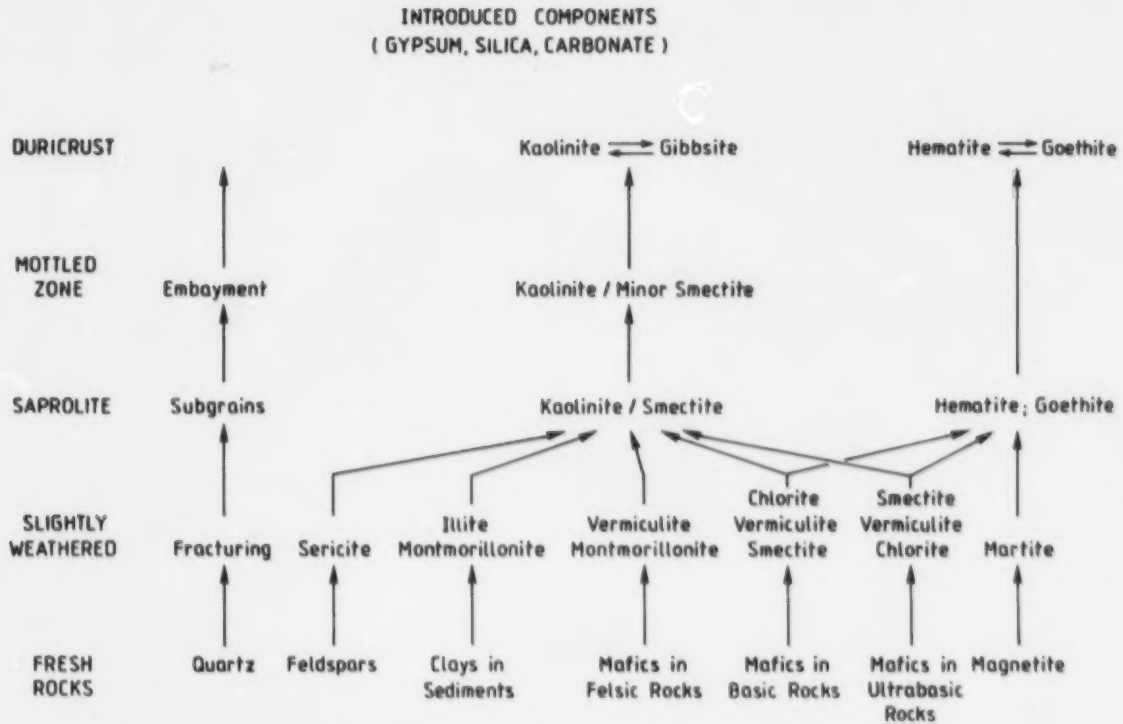


Figure 20.4. Schematic representation of the sequence of minerals developed over different rocks during weathering.

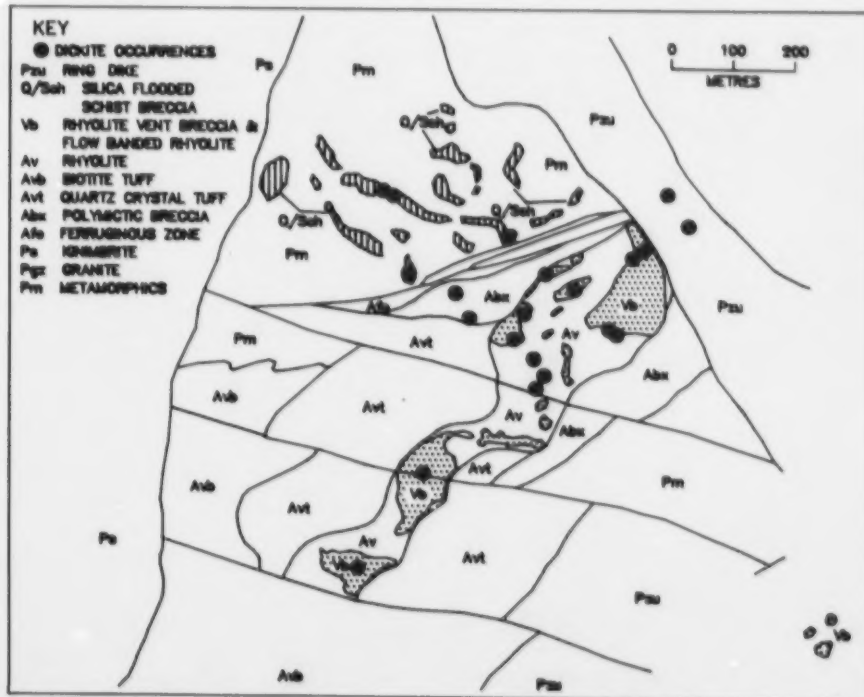


Figure 20.5. Geology map and the dickite distribution map as determined by spectroscopic measurements of field samples for the Anastasia Prospect, northeastern Queensland.

northwest-striking and steeply dipping, silica-flooded breccias with anomalous gold content.

Samples of surface float were collected and examined with a field portable spectrometer. Interpretation of the spectra resulted in the mineral distribution maps for dickite, alunite, jarosite, and muscovite. Dickite, the high-temperature, alteration-related form of kaolinite, is distributed in two belts (see Figure 20.5), one coinciding with the northeast-trending rhyolite and breccias and the other with the northwest-trending silicified ridges in the metamorphics. The alunite and jarosite distributions are likewise controlled by these two alteration zones and, as expected, the spectra of the metamorphics are dominated by muscovite.

Figure 20.6 shows typical spectra of the samples collected at Anastasia. A spectrum of kaolinite is included for comparison with the dickite spectrum.

Clearly, important information about the nature and location of the alteration can be obtained by spectroscopic measurements of the surface. However, the interpretation of reflectance spectra requires special skill in which few geologists are suitably trained. If field portable spectrometer systems are to be used more generally, this process will need to be done automatically. The problem is an obvious candidate for the application of expert system techniques. A number of attempts have been made in

this area (Yamaguchi and Lyon 1986; Huguenin and Jones 1986; Horsfall *et al.* 1987) but much work remains to be done, especially in the analysis of the spectra of mineral mixtures.

From the above it can be seen that spectroscopy of field samples can give useful information for mineral exploration. We next consider how much is lost in measurements from an aircraft or spacecraft.

SIGNAL DEGRADATION

Once we move to a remote sensing system, two major complications arise: the mixing of light from multiple cover types within the instantaneous field of view, and atmospheric interference. To understand these effects we need a model for the remote sensing process.

The amount of light seen by a sensor is a complex function of the structure of the surface and the viewing geometry (Kimes 1983; Woodham and Gray 1987). Typical natural surfaces are composed of vegetation (alive and dead) and rock/soil mixtures. The relative amounts of these components influence the shape of the reflectance spectrum.

However, it is vital to note that the greatest pixel-to-pixel variability in brightness is caused by changes in the geometry of the surface, and that this effect is (to a first approximation) common to all wavelengths.

On a macroscopic scale, the brightness of whole pixels is influenced by the effect of slope and aspect on the illumination conditions but exactly the same effects operate internally to each pixel. Light reaching the sensor comes from a variety of different sub-elements within the pixel. Typical sub-elements would be soil in full or partial shade, vegetation in shade, and fully illuminated soil or vegetation. Pixels where the sensor sees large numbers of poorly illuminated sub-elements will be much darker in all bands than those where the sensor sees only fully illuminated surfaces.

A simple model to represent these effects assumes that the scene is composed of M materials each with reflectance spectrum $\rho_{m,\lambda}$, and that in the i -th pixel the amount of each material seen is determined by an "exposure factor" $e_{i,m}$. Then the amount of light with wavelength λ leaving the surface will be

$$X_{i,\lambda} = I_{\lambda} \sum_m e_{i,m} \rho_{m,\lambda} \quad (1)$$

where I_{λ} is the illumination for a flat surface in the pixel. The value of $e_{i,m}$ will be zero when the sensor does not see any material m , either because there is none in the pixel or because what is there is in complete shadow. The upper limit to its values depends on the geometrical arrangement used when the

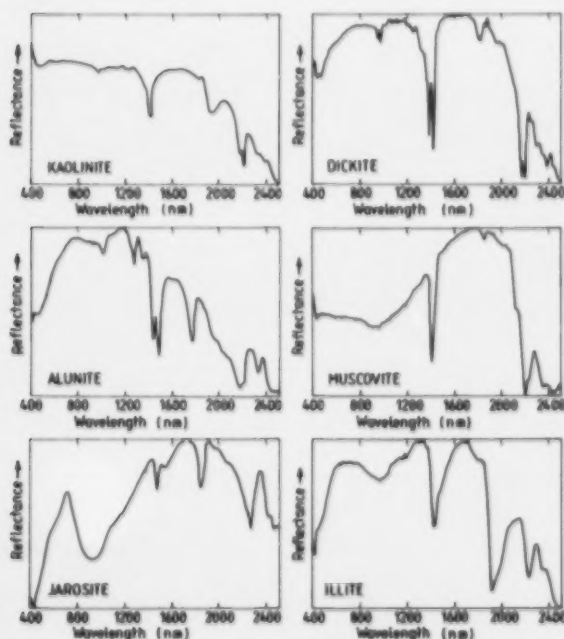


Figure 20.6. Selected spectra of samples of surface float from Anastasia.

$\rho_{m,\lambda}$'s are measured, but will usually be less than 1. It is useful to rewrite (1) by putting

$$e_{i,m} = p_{i,m} E_i$$

where E_i is the length of the vector e_i . Then equation (1) can be rewritten

$$X_{i,\lambda} = I_\lambda E_i \sum_m p_{i,m} \rho_{m,\lambda} \quad (2)$$

and the $p_{i,m}$ can be considered as the "effective proportion" of material m in pixel i .

If we are prepared to drop our concern with the different materials in the scene, we can put

$$\rho_{i,\lambda} = \sum_m p_{i,m} \rho_{m,\lambda} \quad (3)$$

and call $\rho_{i,\lambda}$ the "effective reflectance" for pixel i at wavelength λ .

This then simplifies (2) to

$$X_{i,\lambda} = I_\lambda E_i \rho_{i,\lambda} \quad (4)$$

The above expressions describe the amount of light leaving the surface. By the time it reaches the sensor it has been attenuated due to absorption and scattering processes in the atmosphere and supplemented by light scattered into the field of view of the sensor. A full description of these effects is complicated (Slater 1980) but the major effects can be accommodated within a linear correction to the data. If we combine these atmospheric terms with the optical and electronic gains of the sensor, we can use (3) and (4) to get expressions for the output $Y_{i,\lambda}$ of the remote sensing system.

$$Y_{i,\lambda} = a_\lambda + b_\lambda E_i \sum_m p_{i,m} \rho_{m,\lambda} \quad (5)$$

and

$$Y_{i,\lambda} = a_\lambda + b_\lambda E_i \rho_{i,\lambda} \quad (6)$$

Here a_λ is a product of the atmospheric scattering term and the sensor gain factors while b_λ incorporates the I_λ term, the atmospheric attenuation and the sensor gains.

Figure 20.7 shows the output of an airborne spectrometer for two areas on a flight line near Kamalalda, Western Australia. The raw data $Y_{i,\lambda}$ shown is on the left, the residuals corrected for the b_λ term are on the right. The first area (a) produces no strong features while the second (b) has a soil rich in talc which dominates the residual spectrum. The effect of the different mineral reflectances for the two areas cannot be discerned in the raw data because the b_λ term dominates the shape of these curves. It is only possible to remove this atmospheric variability

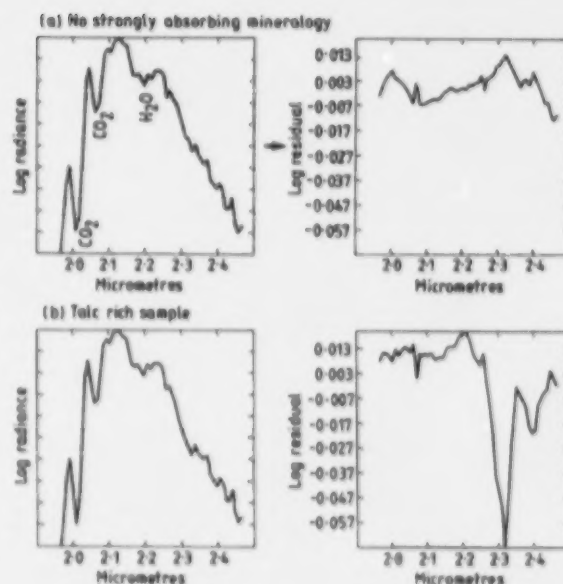


Figure 20.7. Plots of the raw radiance and the associated residual after atmospheric correction for two areas on the same flight line near Kamalalda in Western Australia.

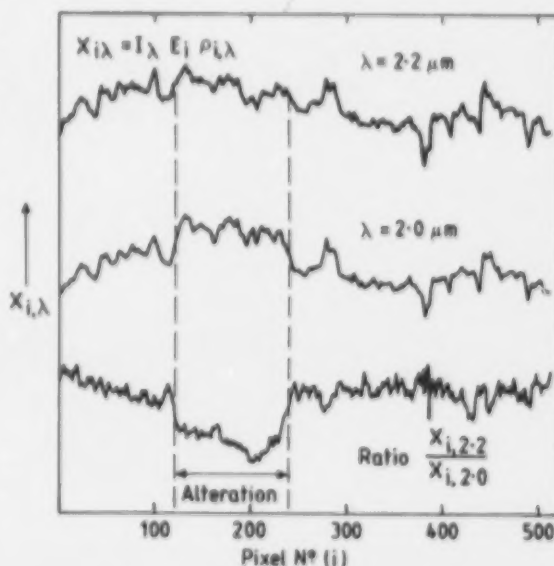


Figure 20.8. Plots of the output of the 2.0 μm and 2.2 μm channels of an imaging spectrometer system over an area of alteration in Nevada.

ity because b_λ is constant for all the samples (i) in the flight line.

Figure 20.8 shows plots of the output from an airborne spectrometer, in two wavelength channels, for a flight line over an area of alteration in the west-

ern U.S.A. One channel ($\lambda = 2.2 \mu\text{m}$) shows decreased reflectance over areas of clay alteration and the other ($\lambda = 2.0 \mu\text{m}$) is unchanged. Both curves have similar shape due to the dominance of the E_i term in equation (6). Because E_i is the same for both channels, we can compute the ratio of the two plots to define the area of alteration. Assuming that the a_1 term is small, this ratio is the ratio of the effective reflectances (equation (3)) in the two channels and is proportional to the amount of absorption in the alteration-sensitive channel.

In areas with little or no vegetation, the ratio technique provides a simple and powerful method for defining regions of differing mineralogy. However, when the vegetation density is variable and appreciable (greater than 20 percent), the pixel-to-pixel variability of the effective reflectance is dominated by the spatial variability of the vegetation. In areas like northeastern Queensland, where the vegetation cover varies from 10 percent to 50 percent, the ratio does no more than map the vegetation. More sophisticated data processing is required to remove this effect.

The multispectral data that these systems generate is a function of location i and wavelength λ . However, as illustrated in Figures 20.7 and 20.8, the major sources of variability are not associated with the mineral reflectances $\rho_{m,\lambda}$ but with the geometric (E_i) and atmospheric (b_1) terms. In areas with vegetation cover, a third source of variability (a function of both location and wavelength) is added. It is an unfortunate reality that the surface mineralogy usually contributes only a small perturbation to a signal dominated by non-mineralogical effects.

If we are to extract the weak mineral reflectance information, a considerable amount of data processing is necessary. This processing can remove the unwanted sources of variability but, if the sensor does not have sufficient signal-to-noise performance, the subtle mineral-related signal can be lost.

This brings us to the source of the last degradations applied to the data, the sensor itself.

RESOLUTION

The performance of a sensor can be described in terms of its radiometric, spectral, and spatial resolution. Increasing any of these parameters increases costs everywhere, from sensor design to data analysis, so it is important to know which of the three is the most important for any particular application.

Radiometric resolution or signal-to-noise ratio is the most neglected but perhaps the most important for mineral mapping. Low noise levels are essential for the recovery of weak mineral signatures from a signal cluttered with atmospheric, geometric, and vegetation variability. The early satellite systems had signal-to-noise ratios of the order of 50:1. Most systems now are more like 100:1 or 200:1 and a few

airborne systems claim performance up to 1000:1 (Slater 1985).

The spectral resolution of a sensor determines the uniqueness with which mineral identification can be made. Systems with high resolution produce curves where closely spaced absorption features can be resolved and accurately located (e.g. see Figure 20.2). This type of data is essential if we wish to distinguish between minerals of similar type. For example, it is not possible to distinguish between kaolinite and montmorillonite without sufficient resolution to detect the short-wavelength shoulder on the $2.2 \mu\text{m}$ absorption feature of kaolinite.

Clearly there is a continuum of possible sensors from high to low spectral resolution, but currently three main types of sensors are recognizable. These, along with their mineral mapping potential, are shown in Table 20.1.

The systems with high spectral resolution measure enough adjacent bands to define a full spectrum. These systems are either line-trace spectrometers or full imaging spectrometers (Marsh and McKeon 1983; Goetz *et al.* 1985b; Vane and Goetz 1986). Both types are currently available only as aircraft-based research systems although imaging spectrometer systems are planned for both the European and USA Polar Platforms in the 1990s (NASA 1986). A number of imaging spectrometer systems operating only in the VNIR are commercially available but, because they lack SWIR capability, they do not have any real potential for mineral mapping.

TABLE 20.1. MINERAL IDENTIFICATION AS A FUNCTION OF SPECTRAL RESOLUTION.

High	Medium	Low
Hematite	Hematite	Iron Oxide
Goethite	Goethite	
Rare Earths	-	-
Calcite		
Magnesite	Carbonates	-
Dolomite		
Kaolinite		
Dickite		
Pyrophyllite		
Montmorillonite	Al-OH Minerals	
Illite	or	
Muscovite	Sulphates	Carbonates
		or
Alunite		Phyllosilicates
Jarosite		or
		Sulphates
Talc		
Chlorite	Mg-OH Minerals	
Epidote		
Amphiboles		
	Felsic Rocks	
	Mafic Rocks	
	Ultramafic Rocks	

The medium resolution systems (Honey and Daniels 1985; Kahle 1987; Fraser *et al.* 1985; Rowan *et al.* 1987) are a new generation of operational and semi-operational scanners with band selection optimized for mineral exploration. They usually have five or six bands in important regions such as the 1.9 to 2.5 μm or the 8 to 14 μm atmospheric windows. They are not capable of the fine discrimination of the high resolution systems (*see* Table 20.1) but are a very significant advance over the low resolution sensors.

The existing operational satellite sensor systems (SPOT and Landsat) represent the low spectral resolution systems. Although they usually provide good vegetation mapping and some capability for iron oxides, only the 2.2 μm band on the Landsat Thematic Mapper offers anything extra for mineral mapping. The TM can indicate the presence of alteration products but can provide no guide as to what they are.

Spatial resolution is usually considered the most important kind of resolution and there has been a continuing evolution of spacecraft sensors towards smaller pixel sizes. This has seen the original Landsat MSS with 80 m pixels evolve through Landsat TM (30 m), SPOT multispectral imagery (20 m) to SPOT panchromatic imagery (10 m).

While good spatial resolution is essential for many structural applications in geology, it is not so critical for mineral identification work. This is because there is no practical pixel size that could eliminate the effects of mixtures of materials within pixels.

DATA PROCESSING

Image processing has become an essential feature of the analysis of modern remote sensing data. This is especially so in the case of mineral mapping as it provides the method whereby the effects of atmosphere, surface geometry, and vegetation can be removed to leave a map of the soil/rock reflectance properties.

In non-vegetated areas (or areas with very uniform vegetation cover) the problem is well understood. Here, it is only necessary to remove the exposure term E_i and the atmospheric terms a_i and b_i to leave the soil/rock reflectance information $\rho_{i,\lambda}$. Two approaches are common: ratio corrections, and co-ordinate transformations.

1. Ratio Methods

The ratio techniques depend on the multiplicative nature of equation (4) but before this can be utilized the data must be corrected for the effect of the a_i term (equation (6)). This can be accomplished by one of several techniques (Switzer *et al.* 1981; Crippen 1987) which depend on extrapolations of the

observed data distribution in the N-dimensional vector space defined by the N wavelength channels.

Once the data have been corrected for atmospheric scattering, ratios between wavelength channels remove the E_i term, and normalization to the channel mean removes the b_i term. Many different ratio methods have been used (Gillespie *et al.* 1987). Where few bands are involved (e.g. Landsat data) it is usual to compute between-band ratios chosen to enhance particular mineral absorption features.

The earliest work in this area took advantage of the low reflectance of iron oxides at blue-green wavelengths to map sulphide weathering products in the western USA (Rowan *et al.* 1974; Segal 1983). Colour ratio composites are normally made of several ratio images where each ratio is chosen to enhance a particular material. With the extended wavelength range of the Landsat TM instrument, clay-rich areas can be mapped using a ratio of the 1.6 μm and 2.2 μm bands (Abrams *et al.* 1977; Podwysocki *et al.* 1983).

In the analysis of higher spectral resolution data, where it is important to extract the shape of the reflectance curve, between-band ratios are no longer a suitable tool. Normalization to the mean value of all channels removes the geometric effects but the effects of the b_i term remain. Ideally one would like to have a standard reflectance target somewhere in each scene which could be used to normalize the data. Usually this is not possible and data are often normalized to some mean spectrum. The logarithmic residual technique of Green and Craig (1985) achieves this by computing the quantity

$$Z_{i,\lambda} = Y_{i,\lambda} Y_{0,0} / (Y_{0,\lambda} Y_{i,0}) = \rho_{i,\lambda} \rho_{0,0} / (\rho_{0,\lambda} \rho_{i,0}) \quad (7)$$

Here $Y_{i,0}$ is the geometric mean of the data over all channels for the i -th pixel, $Y_{0,\lambda}$ is the geometric mean over all pixels for the λ -th channel and $Y_{0,0}$ is the geometric mean over all channels and pixels. The notation for the reflectance terms ρ is the same. This quantity is effectively a ratio to the mean reflectance ($\rho_{0,\lambda}$) used in the absence of a standard in the scene.

Figure 20.9 shows the logarithmic residual spectra from an airborne survey over Mary Kathleen, Queensland. The spectra are averages for the areas where field sample spectra (Figure 20.10) were also collected. The similarities between the airborne and field results are striking.

2. Co-ordinate Transformation Method

Each pixel from a multispectral data set with N bands can be represented as a point in an N-dimensional vector space. Pixels with similar values in all wavelength channels will be close in this space and, assuming the a_i term has been removed, those differing only in the value of $\rho_{i,\lambda}$ lie on a straight line passing through the origin. Because the geometric

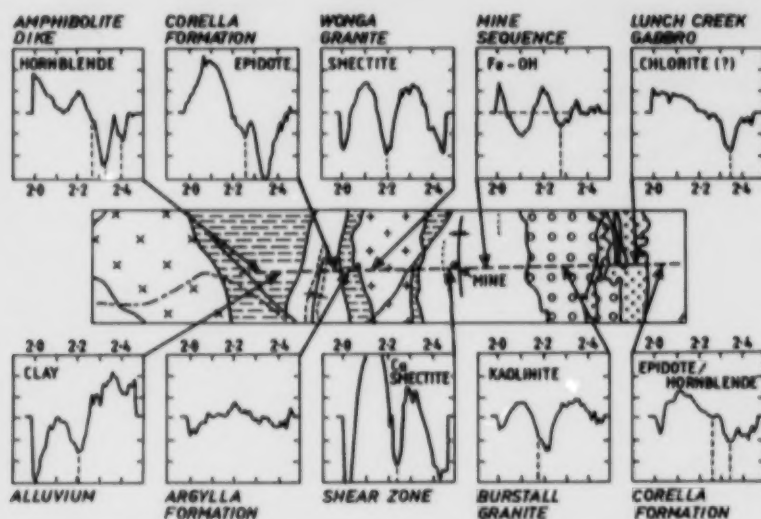


Figure 20.9. Log-residual spectra from airborne spectrometer data collected over Mary Kathleen, Queensland.

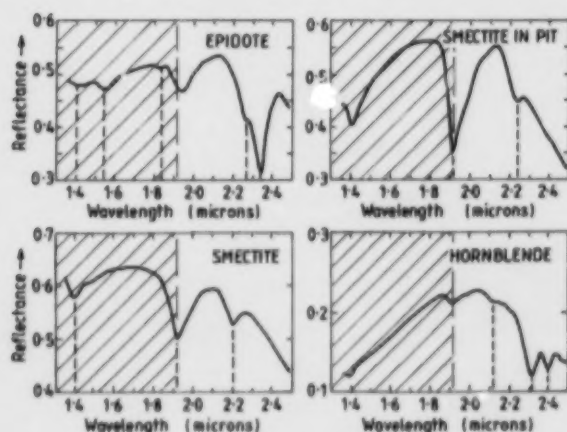


Figure 20.10. Spectra of field samples collected in the Mary Kathleen area, for comparison with the airborne spectra shown in Figure 20.9.

variability is so much greater than the reflectance variability, the data distribution for many poorly vegetated scenes tends to be clustered around such a line. Statistically, this effect shows up as very high between-band correlation.

The co-ordinate transformation methods seek new co-ordinate systems for the vector space in order to separate geometric and reflectance variability. Usually this involves aligning one axis with the line determined by the dominant geometric terms. The data variability in the remaining components is then a function of the more subtle, wavelength-dependent reflectance variations and can be rescaled to enhance these effects. The most important methods

are the Principal Components and HSI transforms, discussed in detail by Gillespie (1986). It is important to note that, because these methods often involve linear combinations of the rescaled data, corrections for the a_1 and b_1 terms are not required.

When the vegetation density becomes appreciable, the ratio and co-ordinate transformation techniques are still useful but they must be interpreted in terms of the mixtures that the sensor is seeing. Although they still remove geometric and atmospheric effects, the effective reflectance $\rho_{1,\lambda}$ recovered is confused with the spectrum of vegetation and is difficult to interpret in terms of soil mineralogy.

In these environments, the aim of the data processing is to strip the effects of the vegetation from the signal to leave, if possible, only the effects of the soils. In principle this is feasible. Usually, there is more information (i.e. wavelength channels) for each pixel than there are materials mixed within it. If the reflectance spectra of the components are known, it should be possible to estimate the amount of each material in the pixel. But this simple concept hides a host of difficulties. How do you determine what components are in the pixel? How many are there? Can they be discriminated with the channels being used? These problems are the subject of research at the moment (Johnson *et al.* 1983; Adams and Adams 1984; Elvidge and Lyon 1985; Fraser and Green 1987) but in some cases it is clear that solutions are possible.

The problem has been most often faced in the analysis of the 2.2 μm band of the Landsat TM instrument. Clay-rich areas have an anomalously low reflectance in this band (see Figure 20.2) and should be detectable. Unfortunately, green vegetation has the same property and it is often impossible

to distinguish the two. The approach of Elvidge and Lyon (1985) and Fraser *et al.* (1986) has been to use the shorter wavelength bands where vegetation is well characterized to provide a measure of the amount of vegetation in the pixel. This measure is then used to "back out" the vegetation effects in the 2.2 μm band, leaving only the soil contribution to the band.

Photo 20.1a is an aircraft scanner image of the ratio of the 1.6 and 2.2 μm TM bands for an area of sericitic alteration near Bald Mountain in northeastern Queensland. Clay-rich areas should show as bright tones on this image but there is no obvious pattern due to the appreciable tree and grass cover. Photo 20.1b is an image of the 2.2 μm band where the vegetation effects have been reduced by using the information in the shorter wavelength bands. This image has been obtained by: a) establishing a multiple linear regression between the 2.2 μm band and all the others, b) using the regression formula to predict the 2.2 μm band, and c) displaying the re-

siduals to the regression. The grey levels of the resulting image were then inverted so that bright areas on this residual image are regions with a reflectance lower than that predicted on the basis of the shorter wavelength bands. Areas of mid-gray are those well predicted by the regression.

Assuming the 2.2 μm band is the only one where the reflectance is affected by the clay content, clay-rich pixels have a reflectance lower than predicted on the basis of the short wavelength bands. Conversely, pixels containing green vegetation are well predicted because the short wavelength bands are very diagnostic of vegetation. As a result, the brighter areas in the centre of Photo 20.1b define the area of alteration and the confusing effects of the vegetation pattern have been removed.

All the techniques described above are seeking to strip major sources of variability from the data to leave only weak mineralogical signals. In this process noise is always enhanced and its removal becomes a serious problem. It is not unusual for a data analyst

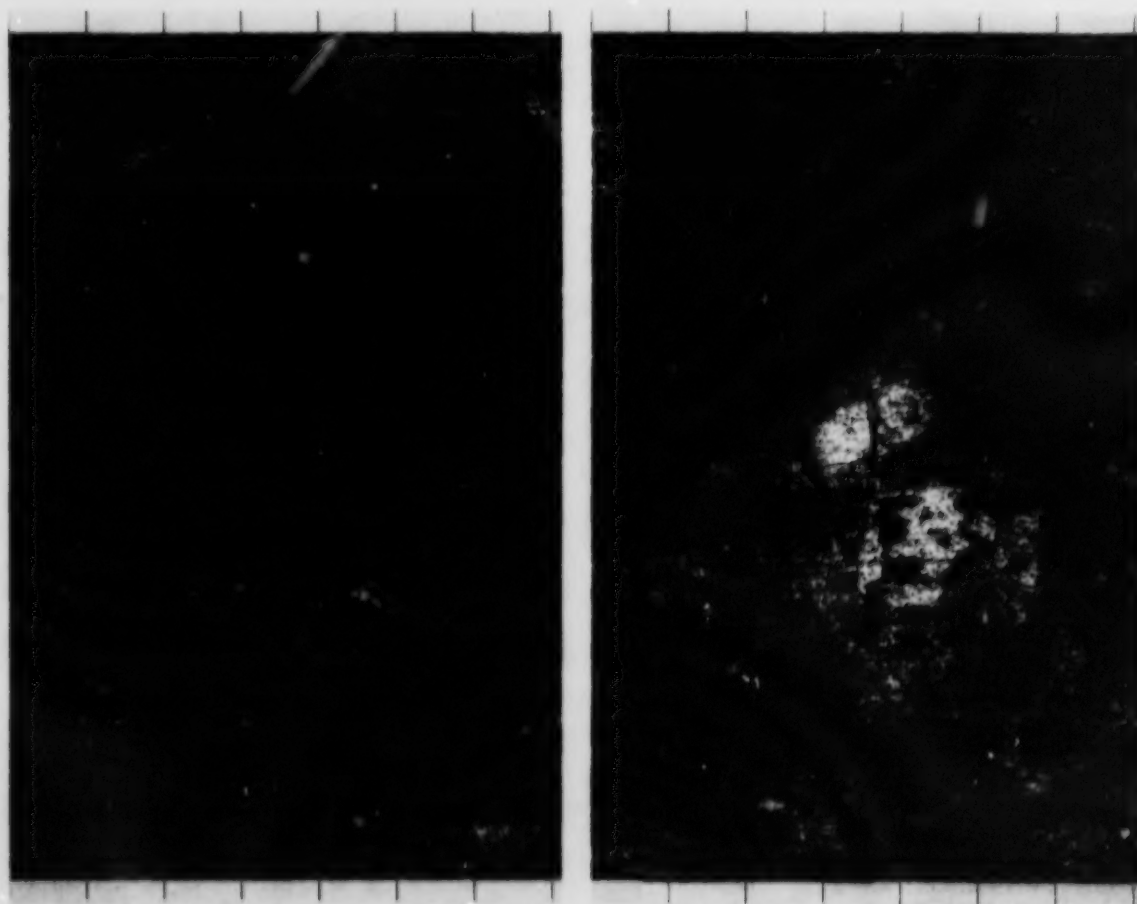


Photo 20.1. On the left (1a): Image of the ratio of the 1.6 μm and 2.2 μm bands of an Airborne Thematic Mapper Simulator over an area of alteration near Bald Mountain in Queensland. On the right (1b): Image of the 2.2 μm band corrected for the effects of vegetation cover.

to devote as much effort to cleaning the data as is expended in the processing described above.

IMPLICATIONS FOR MINERAL EXPLORATION

The three levels of spectral resolution indicated in Table 20.1 determine the extent to which mineral discrimination can be made.

The lower resolution satellite systems with few bands are useful for regional reconnaissance. The Landsat Thematic Mapper can map very large areas to locate regions of increased clay and iron oxide concentration and, in environments with little weathering, can be a powerful tool for the location of alteration.

Plate 20.1 (see Colour Folio near back of book) is a Landsat TM colour ratio image of the arid Yerington mining district in Nevada. Areas of potassic and argillic (clay) hydrothermal alteration appear in yellow-to-orange colours. The red area in the top-right is due to clays on waste dumps from the old Anaconda Yerington porphyry copper mine. The thin, central, yellow zone crossing the image is the O-H-bearing alteration zone of the Singatse Range, now lying on its side and younging towards the left. The yellow altered area in the top-left is the Blue Hills Zone, the faulted and rotated extension of the Singatse Range argillic zone. Other yellow-orange altered areas and some related skarn deposits are also evident in the ranges, in the lower part of the image.

The clarity with which alteration is depicted is not so readily achieved in situations where weathering or vegetation confuse the interpretation. Plate 20.2 (see Colour Folio near back of book) shows the Aircraft TM colour ratio composite for an area east of Christmas Well near Leonora in Western Australia. The colour combination is similar to that used for the Yerington image, with clay-rich areas showing in red-orange-yellow hues and iron-rich areas in green. However, in this image almost all the clay is derived from weathering and is exposed at the margins of a partially dissected, iron-rich laterite surface as halos of saprolitic material. In areas of such intense weathering, interpretation of primary or alteration mineralogy is extremely difficult and can only be done in the context of a detailed understanding of the geomorphology of the region.

Aircraft systems with many more bands than are available on spacecraft systems provide the next stage in the exploration process. They can be used for detailed surveys at the exploration licence level (less than 1000 km²) and, depending on the system, it is possible to learn a certain amount about the nature of any alteration (Marsh and McKeon 1983; Abrams *et al.* 1984; Honey and Daniels 1985). Imagery from the GER 64 band imaging spectrometer system (Collins, President, Geophysical Environmental Research Corporation, New York, personal

communication, 1987) flown over Oatman, Arizona is shown in Plate 20.3 (see Colour Folio near back of book). The area covers 4 by 16 miles, the data have a twenty metre pixel and highlight several areas of phyllic and argillic alteration (Clifton *et al.* 1980) and other lithologies, on the basis of their mineralogy. The most intense phyllic and argillic alteration occur in the top-left, where alunite maps as light blues surrounded by sericite in light green and lime green. Mixed alunite, and sericite or kaolinite map as white. The dark-green area in the top-right is interpreted as a flat-lying phyllosilicate-rich tuff, showing spectra typical of montmorillonite. Background, unaltered terrain appears in deep blue. The central, circular, red area has mineralization and alteration on its margins. It has consistent 2.33 μm absorption and is interpreted as due to a regional chlorite, epidote, and carbonate mineralogy consistent with its basaltic origin or possible propylitic alteration. The spectra in Figure 20.11 were extracted from the image data and show the spectral detail that makes possible the above mineral identifications.

As sensor systems improve in both spectral and radiometric resolution, it will be feasible to discriminate minerals at a new level of sophistication. At this level, now available only by using field-portable spectrometer systems, it will be possible to subdivide the more important mineral species. A good example is the discrimination of dickite from kaolinite. Dickite, a high-temperature form of kaolinite, is usually a product of hydrothermal alteration. In weathered terrain kaolinite is usually a weathering product. Because current remote sensing systems cannot distinguish the two, it is difficult to tell weathering from alteration. High resolution SWIR spectroscopy can make the distinction, and as a result has great potential for exploration.

There are a number of other situations where high spectral resolution will be important. The identification of iron-substituted kaolinites and smectites (Raines *et al.* 1985) and the mapping of the iron/magnesium ratios in chlorites (McLeod *et al.* 1987) are but two. As more research is done into the spectroscopy of minerals there is no doubt that more important applications will emerge.

CONCLUSIONS

Remote sensing can be a powerful tool for mapping the surface distribution of minerals. However, it must not be used blindly. Vegetation cover and intense weathering pose serious limitations because the material exposed at the surface is no longer related to lithology.

In situations where mineralogy of interest is partly or fully exposed to the sensor, useful information can be obtained. But careful data processing is necessary to remove the much greater variability induced by atmospheric, geometric, and vegetative factors.

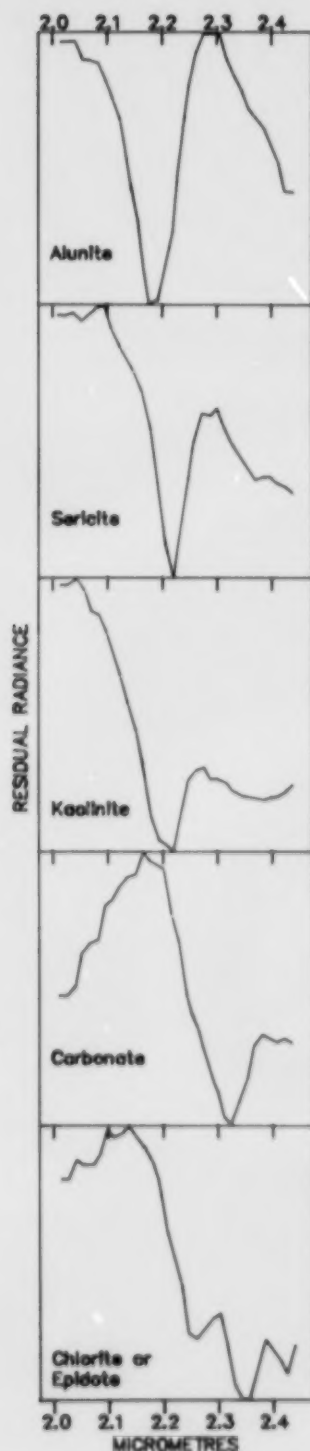


Figure 20.11. Thirty-two channel, log-residual spectra extracted from specific parts of Plate 20.3, and their mineralogical interpretation.

The greatest potential for these systems lies in the location of alteration minerals and in the sophisticated discrimination of different types of alteration products. To achieve this, sensor systems need to improve still further in their radiometric and spectral performance but, if developments in the past ten years are any guide, by the time of the Exploration '97 conference we should be close to this goal.

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21. Regional Airborne Gamma-Ray Surveys: A Review

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ABSTRACT

High sensitivity, quantitative, airborne gamma-ray spectrometry has been applied extensively since the mid-1970s in support of geological mapping and mineral exploration.

The method depends upon the fact that absolute and relative concentrations of the radioelements, K, U, and Th vary measurably and significantly with lithology. Surveys undertaken in Greenland, North and South America, Africa, Australia, and Europe show that the method is applicable to surface mapping in all types of environment. The method is very effective at subdividing acid igneous and metamorphic rocks in hitherto poorly mapped Shield areas wherever they are not masked by impermeable transported cover. It highlights those rock types characterized by unusual amounts or proportions of radioelements such as peralkaline, carbonatite, and ultrabasic complexes.

Airborne gamma-ray spectrometry surveys can be of direct assistance to exploration for many commodities, most obviously for U and Th, but commonly also for Sn, W, REE, Nb, and Zr. Less often, but of importance in specific circumstances, radiometric anomalies can point to Au, Ag, Hg, Co, Ni, Bi, Cu, Mo, Pb, and Zn mineralization, either because one or more of the radioelements is an associated trace constituent or because the mineralizing process has changed the radioelement ratios in the surrounding environment.

The biggest technological development since 1977 has been the introduction into data-processing of computer-controlled colour plotters and in particular their use for the production of three-element (ternary) colour maps. This has facilitated the rapid assessment of data, correlation with other geoscientific information, and subsequent interpretation.

So far only limited use has been made of the quantitative data which have been collected by several large national surveys.

INTRODUCTION

In 1967, airborne gamma-ray spectrometry was a qualitative prospecting technique which was beginning to be used for uranium exploration. The equipment was insensitive and tended to be unreliable. By 1977, much improved high-sensitivity instrumentation had been introduced and the procedures

whereby reproducible quantitative data could be obtained were well established. The method had become a primary tool for uranium exploration. Large systematic surveys were conducted in several countries in the period from 1975 to 1979 in support of national energy programs, for example in Canada (Uranium Reconnaissance Program), USA (National Uranium Resource Evaluation), and Sweden. The decade since 1977 has seen fewer technological innovations and a reduced rate of data acquisition, but it has allowed time for the broad applicability of the technique to geological mapping and general exploration to be demonstrated in a wide range of environments. It is interesting to note that Morley (1969) commented that:

"...the information gained (from the use of the airborne gamma-ray spectrometer as a mapping device) would be rather specialized and not at present susceptible to interpretation in terms of a geological map. The method is not capable of penetrating surficial cover so that no information on the nature of the bedrock is obtained over drift-covered areas."

Since that time, surveys totaling many millions of square kilometres carried out on all continents (except Antarctica) have demonstrated that this statement requires careful qualification, and that in many situations the technique is probably more useful than any other single airborne geophysical or remote sensing technique in providing information directly interpretable in terms of surface geology.

Although airborne gamma-ray spectrometry is a technique dependant on physical phenomena, the results obtained are, for geological and exploration purposes, best considered in geochemical terms. Thus, the technique provides a fast method of undertaking a ground-level geochemical survey from the air. This was first demonstrated by Darnley and Grasty (1971). As with any other type of surficial geochemical survey, the method indicates the composition of whatever material forms the surface. Its relationship to the composition of bedrock must be inferred from consideration of complementary evidence, provided by geological maps, air photos, satellite imagery, or ground inspection.

The most significant technical innovation of the past decade in exploration technology has been the introduction of automated colour plotters in the digital data compilation process. The application of this technique to airborne gamma-ray survey data has made it possible to produce maps which simulate, and, in some important respects enhance the information provided by a conventional geological map.

It is only feasible in this short review to consider the applications of airborne gamma-ray spectrometry.

*Geological Survey of Canada Contribution Number 21888.

try directly related to geological mapping and mineral exploration. However, it should be noted that a sensitive, properly calibrated, airborne system can be used for identifying and monitoring (in real-time when required in emergency situations) atmospheric radioactivity, radioactive contamination of the ground (Bristow 1978) and, by measuring the attenuation of natural ground-level radioactivity, it can estimate snow-water depth for hydrological purposes (Grasty 1980).

METHODOLOGY

The principles of airborne gamma-ray spectrometry have been described elsewhere (Grasty 1979; Bristow 1983). Developments over the past decade have included more widespread use of upward-looking radiation detectors for measuring atmospheric radon (Geometrics 1979), and refinements in data reduction methods (Grasty *et al.* 1985).

The term "regional surveys" as used in this paper refers to surveys covering areas of the order of several tens of thousands of square kilometres, typically requiring either the work of more than one airborne system, or with data acquisition spread over more than one season of work. In either situation, in order to compile the results without any artificial discontinuities, it is essential to have the means of standardizing data collected over a period of time. For example, the radioactivity map of Canada (Darnley *et al.* 1986), which covers an area of 2.7 million km², is based on data collected by five different aircraft systems over a 13-year period (1971 to 1984). Data consistency was maintained through the use of the Geological Survey of Canada's calibration facilities in Ottawa, constructed in 1968 (Darnley 1970). The method of calibration, accepted by the International Atomic Energy Agency (IAEA) in 1976 (International Atomic Energy Agency 1976), has since been adopted in nine other countries (China, Finland, India, Israel, South Africa, Sweden, Thailand, Turkey, and the USA). For a detailed account of current practice see Grasty (1987). The existence of these calibration facilities (and possibly others which have not been reported), now makes it possible for radiometric surveys in almost all parts of the world to be standardized and reported in the units recommended by the IAEA, i.e. percent K, parts per million eU, parts per million eTh, and for total count, Units of Radioelement Concentration.

GEOCHEMICAL DISTRIBUTION OF RADIOELEMENTS AND THEIR GEOLOGICAL SIGNIFICANCE

The usefulness of airborne gamma-ray spectrometry as a geological mapping and exploration tool hinges on two factors:

1. the extent to which the distribution of the radioactive elements relates to differences in the lithology of common rocks, and the extent to which these are recognizably modified by mineralizing processes
2. the extent to which the radioelement content of bedrock is reflected in the composition of surficial materials which can be spatially related to their bedrock source

Unless there are detectable compositional differences between lithologies, and these differences are retained in surficial materials, the method cannot be effective.

Wherever surface material consists of impermeable transported alluvium, lacustrine or marine silts or clays, clay till or aeolian sand, the method can only indicate the geochemistry of these materials and not that of underlying bedrock.

RADIOELEMENTS IN BEDROCK

The distribution of radioelements in common rocks is tabulated by Killeen (1979), also IAEA (1979).

Potassium is the ninth most abundant element in the earth's crust; most K occurs in potassic feldspars and micas, which because they are widely distributed but vary in amount, are one of the diagnostic criteria in the geological classification of rocks. Whilst U and Th are trace elements, four orders of magnitude less abundant than K, in common types of igneous rocks they tend to increase sympathetically with K and Si.

Figure 21.1a, based on Galbraith and Saunders (1983) and Ford and Carson (1986), shows the increase in average radioelement composition from ultra-basic to acid igneous rocks, i.e. with increasing silica content. Note that Th shows the biggest rate of increase. Towards the end of the igneous rock differentiation process, represented by leucogranite on this schematic diagram, as temperature decreases, U and Th no longer increase sympathetically. These facts are emphasized by the ratio plot in Figure 21.1b. This shows that U/K and U/Th are relatively constant, although U/Th increases at the leucogranite end. The plot of Th/K increases as far as point A, which represents average granite, then diminishes rapidly, with considerable variability towards leucogranite.

Ratio measurements are particularly useful in airborne gamma-ray spectrometry because they are less affected by source geometry and surface variability than are the total count and individual element data. Terrain clearance corrections are applied to all the radioactivity measurements, so deviations from the nominal clearance are not a factor (IAEA 1979).

The geochemical separation of potassium, uranium, and thorium at the low temperature end of igneous rock differentiation occurs because uranium, which has two valency states, is much more mobile under low temperature oxidizing conditions

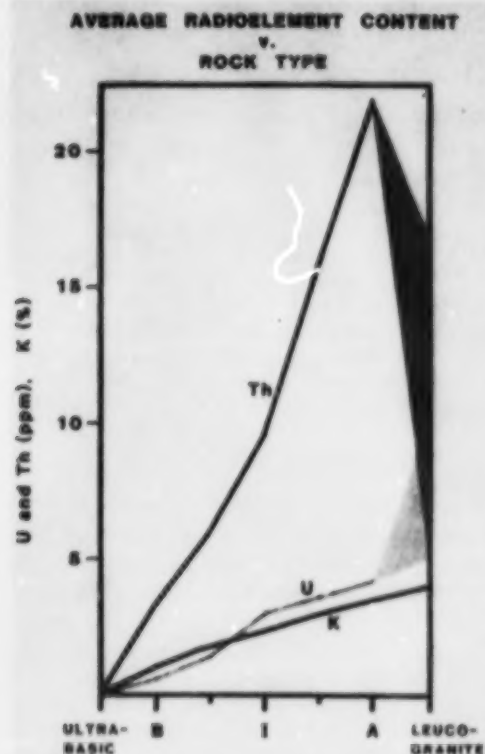


Figure 21.1a. Variation in average K, U, and Th contents with increasing Si content, from ultrabasic to acid igneous rocks (from Galbraith and Saunders 1983; Ford and Carson 1986).

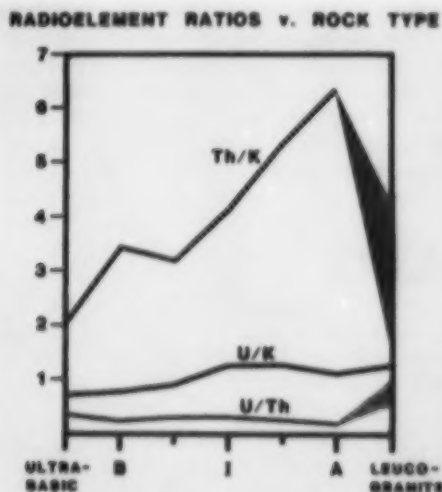


Figure 21.1b. Variation in average radioelement ratios with increasing Si content, from ultrabasic to acid igneous rocks.

than are thorium and potassium. This separation takes place under the conditions of pegmatite formation and is more pronounced in hydrothermal vein systems, where thorium minerals rarely occur and uranium minerals are typically devoid of thorium. In

less siliceous rocks formed at higher temperatures, there are isomorphous U-Th minerals with extensive substitution, for example, the thorianite-uraninite series.

The chemical differences between the two elements result in the further separation of U and Th wherever rocks are subjected to chemical weathering and this is reflected in the composition of mature sediments such as quartzites, which on average are relatively Th-rich, and chemical precipitates, such as limestones, which are relatively enriched in uranium.

Immature sediments, such as arkoses, greywackes, and shales, are compositionally closely related to the rocks from which they are derived, and this applies to their radioelement content.

The metasomatic and hydrothermal alteration processes associated with the formation of various types of mineralization involve the passage of large volumes of fluids which can modify the composition of all types of rocks penetrated by the fluids. These changes commonly involve the alkali elements, with an increase or decrease in K relative to the starting material. Hydrothermal processes constitute a lower temperature, more hydrous extension of late-magmatic alteration, accompanied by fluctuating changes in T, P, pH, Eh, and the ion content of solutions. Under these conditions, U-bearing minerals are particularly susceptible to dissolution, with transportation and redeposition of U spatially separated from the K and Th in the original parent environment.

RADIOELEMENTS IN SURFICIAL MATERIALS

Because a small thickness of overburden absorbs the radiation emitted by the bedrock, airborne gamma-ray spectrometry is correctly described as a surficial mapping technique. Approximately 95 percent of the measured gamma radiation is emitted from the upper 0.5 m of the ground (Gregory and Horwood 1961). Fortunately, this does not limit the usefulness of the method to areas with extensive outcrops, or where there are thin residual soils in temperate climatic zones. It also functions as a bedrock mapping system in areas with glacial till, or thick tropical weathering. It is effective for the same reasons that soil geochemistry is widely effective. It responds to the bulk K, eU, and eTh composition of the surface layer and the composition of this layer is, except for alluvial or lacustrine plains, or over aeolian sand, strongly influenced by the composition of adjacent underlying material. The magnitude of the problem with respect to glaciated terrain, typical of the southern Canadian Shield, was investigated at the beginning of the development of gamma-ray spectrometry in Canada (Darnley and Fleet 1968; Darnley 1970), and found to be less restrictive than anticipated. This has been well substantiated by the results of subsequent surveys, of which a few examples are illustrated in this paper. Gregory (1983) noted that on

the margin of the Athabasca Basin, the gamma-ray spectrometer response over ground moraine closely defines the position of the pre-Athabasca unconformity.

Other studies have shown that the main mass of glacial till is typically locally derived, often within a few hundred metres, and seldom more than 1 or 2 km from its bedrock source (Shilts 1976). Thus glacial transportation of surficial material will result in the features mapped by a surface survey being somewhat displaced from their bedrock sources, and somewhat diluted in intensity, but usually not so far that a ground follow-up investigation cannot pinpoint the sources. Where bedrock, e.g. a carbonatite, is both compositionally distinctive and relatively friable, the dispersal train may be traceable for many kilometres, which assists in studying the dispersal process as well as finding the source (Ford *et al.* 1987).

Evidence with respect to the effectiveness of surveys over tropical rain forest, in drier tropical areas such as northern Australia, and desert areas such as in the Middle East, is largely empirical. Some examples are illustrated in this paper.

Tropical weathering is generally dominated by vertical wastage of bedrock, entailing alteration of minerals and removal of soluble components (Rose *et al.* 1979). The original mineralogy of the rock and the distribution of the radioelements within these minerals strongly influences the residual radioactivity of the surface layer. Potassium, U, and Th are mostly contained in relatively chemically resistant original constituents, although some U may be interstitial and this is easily removed. Potassic feldspar and muscovite weather slowly to form illite, a K-rich clay. Uranium and Th are commonly constituents of weathering-resistant accessory minerals such as zircon and monazite. For a comprehensive review see Butt and Smith (1980).

SURVEY DATA

It has been customary for major organizations producing airborne gamma-ray spectrometry data to provide both profiles and maps. Profiles present edited, fully corrected data in greater detail than it is possible to provide in map form. In conjunction with edited digital records, profiles constitute the primary information source.

PROFILES

Profiles are normally compiled on a flight-line/map sheet basis. For each flight-line it has become standard practice to display the following parameters in "stacked profile" form, quantifying the units according to IAEA recommendations (IAEA 1976):

1. total Count (in units of radioelement concentration, abbreviated Ur)

2. potassium (in percent)
3. equivalent uranium, eU, (in ppm)
4. equivalent thorium, eTh, (in ppm)
5. eU/eTh ratio
6. eU/K ratio
7. eTh/K ratio

It has become increasingly common to include aeromagnetic and VLF-EM data with the stacked profiles in addition to the terrain clearance and ground-track data normally provided. In mountainous terrain, barometric altitude is also recorded. Profiles are usually produced at scales of 1:250 000 or 1:50 000. For reasons of economy 1:20 000 is not used for any survey of a large area.

MAPS

In order to display regional trends and contrasts the above parameters are presented in map form. Several different approaches have been taken to map compilation.

The production of a contour map normally entails considerable smoothing of profile data. It may also entail line-to-line leveling if, for example, background corrections are imperfect, or ground moisture conditions change during data collection. Preliminary or reconnaissance survey data is sometimes presented as profile maps, to expedite compilation. Where flight lines are far apart, greater than 5 km, for example in the "quick-look" reconnaissance of the District of Keewatin in northern Canada where 25 km spacing was employed (GSC 1975), this is the only satisfactory format. At 5 km spacing, considerable along-line smoothing is required to compensate for lack of line-to-line continuity of detail. Contouring such data can result in the elimination from the map of some possibly important narrow features. Hence, it is prudent also to examine the original profile data from which it has been compiled.

A scale of 1:250 000 has been commonly used for compiling maps flown with a line-spacing greater than 1 km; at this and closer line-spacings, a 1:50 000 scale or even a 1:20 000 scale is required.

COLOUR

The advances that have occurred in the application of airborne gamma-ray spectrometry in recent years are largely the result of the use of colour for presentation purposes. In general, radiometric maps, because of the limited range of the parameters, rarely show the steep gradients and close contour spacing seen on many aeromagnetic maps. For this reason, radiometric trends and level changes are often not obvious unless the maps are coloured. However, for reasons of cost it is not yet standard practice to publish colour maps for each of the seven parameters listed above.

Colour selection is an important consideration because the human eye discriminates some shades

more easily than others. Depending on the area and features of interest, it is desirable to be able to change and modulate colours to ensure no significant features are missed. This is most easily done using a colour video screen in conjunction with an image analysis system.

The main advantage of colour is that it permits the simultaneous display of up to three parameters on one image, facilitating the correlation and delineation of areas based on subtle differences in numerical values. Fewer maps need be handled. The Geological Survey of Sweden was the first organization to publish three-component airborne gamma-ray spectrometry data by assigning a different colour to K, eU, and eTh and using an automated plotter to produce colour profile maps (Linden and Akerblom 1977).

The method of using colour to convey information has evolved considerably since 1977. Several techniques have been devised to portray the three-component information; the simplest is to establish a linear correlation between colour intensity and element concentration. This has the disadvantage for most lithologies of producing rather indistinguishable colours, pastel shades at low concentrations and browns and purples at high concentrations, so that the potential benefits of using colour are not fully achieved (Richardson 1983; Carson, Geophysicist, Geological Survey of Canada, Ottawa, personal communication, 1987). Duval (1983) calculated the ternary ratio of K, eU, and eTh for each grid point on the map and plotted according to a linearly related colour scale. This also suffers from the disadvantage that it does not discriminate effectively within the range of the most commonly occurring values.

The most satisfactory product so far devised from a user's point of view is to use a non-linear relationship between colour and ternary ratio to provide the greatest variation of colour within the range of most frequently observed ratios. Total radioactivity information is added to the image by varying the colour saturation at each point according to the corresponding total count value (Broome *et al.* 1987). This is done because the lower the concentration levels, the greater the statistical uncertainty in the primary radioelement measurements, and the greater the scatter in the ratio values. These three-component compilations are commonly referred to as ternary maps.

APPLICATION TO GEOLOGICAL MAPPING

GENERAL COMMENTS ON INTERPRETATION

The advantages and limitations of total count, single element, and ratio measurements for interpretation purposes, and the constraints imposed by uncertainties in atmospheric background correction, changes in percentage outcrop, surface geometry, ground moisture content, radioactive fall-out, etc., have

been covered in earlier publications (Darnley 1972, 1973; Grasty 1979; IAEA 1979).

The usefulness of airborne gamma-ray spectrometry as an aid to geological mapping is determined by the extent to which the various parameters add significant information to the features normally distinguished on a geological map.

The major advance of the past decade has been the introduction of ternary maps, but it should be noted that these only provide qualitative information and are best used in conjunction with the quantitative data which are available from controlled, calibrated surveys. Although some major surveys have presented all data in the recommended quantitative form, utilization has been slow, and so far only a few organizations have exploited this information.

Galbraith and Saunders (1983), have undertaken an analysis of a large amount of airborne gamma-ray spectrometry data collected under the US National Uranium Resource Evaluation (NURE) program and have illustrated this with respect to the lithologies of the Basin and Range region of the USA. They have shown that a classification based on a plot of $\log_{10}$ Th versus K can subdivide the igneous rocks of this region into conventional groupings. It has been reported previously (Charbonneau *et al.* 1973; Gregory 1983) that eTh/K ratio maps can be very effective at delineating certain geological units.

Harris *et al.* (1987) have described and illustrated the application of statistical analysis, used in conjunction with an image analysis system, to airborne gamma-ray spectrometry data from Nova Scotia. A clustering technique creates images with clearly defined class boundaries and provides statistical information about each class.

The value of any given data set for interpretation purposes is almost always increased if it is used in conjunction with complementary data sets. Examples of the combined use of satellite imagery, aeromagnetic, and airborne gamma-ray spectrometry data have been given by Gregory and Moore (1981), Gregory (1983), and Slaney (1985). Darnley (1982) correlated gamma-ray and gravity data. Corresponding geological maps must be regarded as a standard reference item for all interpretations.

The following sections provide a few examples of the variety of results obtained from surveys completed in the past decade.

HIGH LATITUDE (OR ALTITUDE) MOUNTAINOUS TERRAIN

The ideal situation for the application of airborne gamma-ray spectrometry is a region with a large amount of outcrop and minimal chemical weathering. South Greenland provides such an example.

Plate 21.1 (see Colour Folio near back of book) is a K map produced by the Geological Survey of

Greenland, covering an area of approximately 15 000 km² adjacent to the Greenland ice cap consisting of a rugged coastal strip cut by many fjords. This survey was carried out using a fixed-wing aircraft flying at incremental contour levels. This is an area of Precambrian metamorphosed igneous and sedimentary rocks penetrated by late Precambrian ring complexes of the Gardar Alkaline Province (Geological Survey of Greenland 1975). The airborne gamma-ray spectrometry system was calibrated, enabling results to be expressed as concentration units. The maximum values obtained were 4 percent K, 15 ppm eU, and 40 ppm eTh. The modal values are 1 percent K, 2 ppm eU, and 5 ppm eTh. The K map appears to provide the best correspondence with the geology (Geological Survey of Greenland 1975), whilst the U and Th maps identify the most evolved alkaline centres. Plate 21.2 shows the eTh map.

POST-GLACIAL TERRAIN

In a number of respects, most of the land surface of Canada presents the "worst case" situation for airborne gamma-ray spectrometry because of the extensive surficial cover resulting from recent glaciation. A secondary adverse consequence of glaciation is the presence of much surface water and poorly drained land resulting in reduced surface radioactivity.

Two regions have been selected as examples of the effectiveness of airborne gamma-ray spectrometry notwithstanding the difficulties created by Canadian conditions.

The Quioch River region is in the District of Keewatin on the northwestern side of Hudson Bay, partly within the Arctic Circle. Plate 21.3 is a ternary map based on a 1:1 000 000 compilation of reconnaissance survey data with a flight-line spacing of 5 km (Geological Survey of Canada 1984). The overprinted geological information is taken from the 1:5 000 000 map of Canada (Geological Survey of Canada 1968). It shows a basement complex of Archean gneisses containing enclaves of sediments and volcanics, intruded by younger granites. The ternary map shows that considerable subdivision of the gneisses is possible based on pronounced differences in radioelement content.

The Province of Nova Scotia on the eastern seaboard of Canada provides a good example of the application of airborne gamma-ray spectrometry to a mixed igneous/metamorphic/sedimentary glaciated terrain of late Precambrian-Palaeozoic age. The data shown in Plates 21.4, 21.5, and 21.6, covering an area of approximately 40 000 km², were collected by the Geological Survey of Canada between 1976 and 1986 at a line spacing of 1 km. These figures show the K, eTh/K, and ternary radioelement distributions, with the geology (Keppie 1979) displayed in Plate 21.7 for comparison.

A variety of large- and small-scale features are defined to varying extents in each of the three figures. For example, the K map distinguishes most of the granitic rocks, however, the restricted range of concentration limits further subdivision within the granites in contrast to several of the other parameters (Ford and O'Reilly 1985; Corey 1987). There is also some distinction between the arenaceous and argillaceous formations of the Meguma Group, as well as some apparent further subdivision within the argillaceous formations. Where the former abuts on granite, the K content does not distinguish between them.

Most of the granites are more clearly defined by the eTh/K ratio, although not all granites are readily identifiable. The eTh/K does not separate other geological units with the exception of several of the Carboniferous sedimentary units to the north. The ternary radioelement map of Nova Scotia (Plate 21.6) appears to provide the greatest number of subdivisions compared with any other single map. However, as emphasis is placed on discriminating small differences within the range of most frequently observed ratios, some crucial information that occurs at the upper and lower ranges of the data may become less apparent. This is illustrated in Plates 21.8a and 21.8b, an enlargement of the region surrounding the East Kemptonville tin deposit. Internal variations within the host granite that are apparent on the eU/eTh ratio map and point directly to the deposit are not apparent on the ternary map.

Over the region as a whole, the total count map (not illustrated) is a blander, statistically less "noisy" version of the K map, but it provides the least satisfactory correlation with geology because it cannot discriminate between the radioelements.

EQUATORIAL REGIONS

Plates 21.9a, 21.9b, 21.9c, and 21.9d illustrate radiometric and aeromagnetic data from Central Brazil, an area of tropical weathering and residual soils, extending from 5°S to 16°S. The radiometric and aeromagnetic data for this area were obtained simultaneously and comparison of the maps shows how well magnetic and radiometric data complement one another; at this scale the magnetic map emphasizes deep crustal structure whilst the radiometric map delineates surface lithology. For display purposes the area is divided into two halves. The survey, covering approximately 375 000 km², was flown at a mean terrain clearance of 150 m, with a line spacing of 2 km, reduced to 1 km over one third of the area (Ministerio das Minas e Energia, Departamento Nacional da Producao Mineral 1977).

The northern half of this area (Plates 21.9c and 21.9d) is covered by the Amazonian rain forest. These results demonstrate that despite tropical weathering, contrasts in the surface radioelement concentrations are sufficient to discriminate effectively between formations. Note that overlying

younger geological formations parallel to the north-eastern margin of the area have a distinct radiometric signature, but are magnetically transparent at this scale. Plates 21.9a and 21.9b illustrate the ability of airborne gamma-ray spectrometry to provide structural information. Wherever major structural breaks result in the juxtaposition of dissimilar rock types, any associated abrupt change in the radioelement composition of overlying surficial material can be readily detected by gamma-ray spectrometry. A northeast-trending graben structure is clearly defined by the total count map (Plate 21.9b), as clearly as by the magnetic anomaly map of the same area (Plate 21.9a). A comparison of these figures also shows that the radiometric map is effective at delineating the large ultrabasic bodies in the vicinity of Nickelandia.

Some of the most impressive spectrometric survey results have been obtained in Central Africa. These include a large survey (220 000 km²) over equatorial rain forest in Gabon, which required the use of both fixed-wing aircraft and a helicopter. Guillemot (1987) has published examples of colour compilations of radiometric and magnetic data from this work, with matching geology. A ternary map format is used for the K-U-Th data.

In Rwanda, an intensively cultivated country, with steep slopes and topographic relief of thousands of metres adjacent to one of the Central African Rift Valleys, an area of approximately 20 000 km² has been surveyed entirely by helicopter (Munyagatanga 1987). Plate 21.10 is a reproduction of a ternary map covering the western half of Rwanda. Figure 21.2 is a generalized geological map for the same area (IGNB 1981). Although there are no calibration facilities close to Rwanda, the survey results have been reported in concentration units. It is of interest to note that despite the extreme contrast in weathering conditions, surface radioelement concentrations appear to be comparable to the Greenland survey results referred to above. In Rwanda maximum values reported were 2.4 percent K, 16 ppm eU, and 30 ppm eTh, with modal values of 0.8 percent K, 5 ppm eU, and 13 ppm eTh. Thus in Rwanda, average K appears to be lower, with eU and eTh higher than in Greenland.

Malawi is another Central African country in which extensive gamma-ray and magnetic surveys have been completed recently using both fixed-wing aircraft and helicopters, and where a ternary map compilation of radiometric data, in conjunction with an interpretation of the accompanying magnetic features, has provided a basis for revising existing geological maps (Misener 1987).

SEMI-ARID AREAS

Regions with residual soils and dry climates are very suitable for the application of airborne gamma-ray spectrometry. Smith (1985) has published a ternary

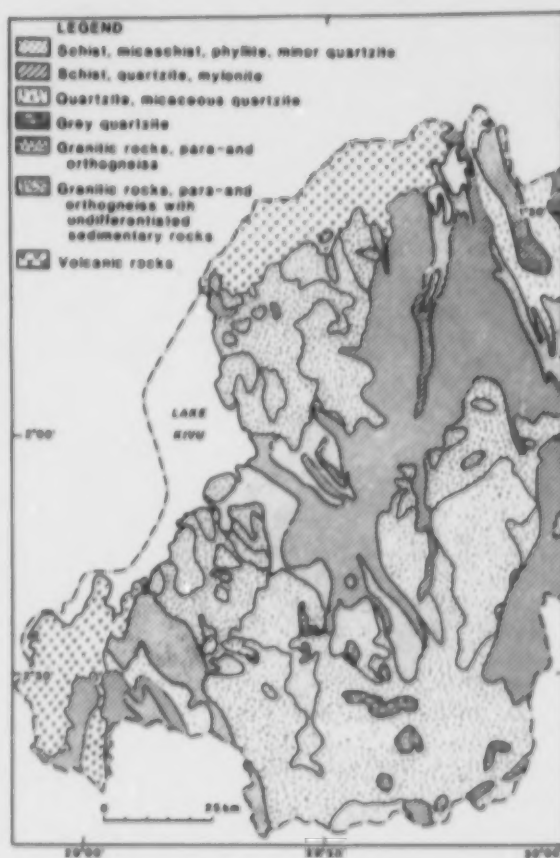


Figure 21.2. Generalized geology, Rwanda (western half), derived from Institut Geographique National de Belgique (1981).

image which is an excellent illustration of how closely a very detailed survey, with a 250 m flight-line spacing, can define complicated fold and fault structures over a 2100 km² area in the Mary Kathleen district of northern Queensland, Australia. Irvine (Geophysicist, BHP Minerals Exploration, Camberwell, Australia, personal communication, 1987) has provided illustrations (not reproduced) demonstrating how effectively the method distinguishes between volcanic ring complexes penetrating 2000 km² of complex Precambrian basement in the Newcastle Ranges of northeastern Queensland.

APPLICATION TO RESOURCE EXPLORATION

URANIUM EXPLORATION

The application of airborne gamma-ray spectrometry to uranium exploration has been described in many publications, e.g. Darnley *et al.* (1977). In brief, the method can provide three important pointers to uranium deposits, the first two delineating re-

gions with good potential, the third delineating targets:

1. Uranium deposits tend to occur within or marginal to areas of the crust which are somewhat enriched in U.
2. Regions which have been subjected to chemical weathering and served as source areas for sedimentary U deposits may exhibit a lower than normal eU/eTh ratio (Galbraith and Saunders 1983).
3. Economically important uranium deposits are characterized by abnormally high eU/eTh ratio values; any enrichment in uranium sufficient to form discrete uranium minerals will result in a distinct increase in both this ratio and eU/K. The latter ratio is a particularly sensitive pointer if uranium mineralization is accompanied by sodium metasomatism, but because eU/K ratio anomalies are more numerous than eU/eTh anomalies, they are of less practical significance in uranium exploration. The eU/K ratio is effective at locating many pegmatoid rocks, which are considered in the following section.

GRANOPHILE ELEMENT EXPLORATION

Quite independently of any significance with respect to uranium mineralization, potassium, uranium, and thorium as trace elements are able to serve as pointers to mineralizing processes.

Most mineralization takes place at temperatures below that at which granitic rocks are formed, and involves the passage of large amounts of fluids. The differential mobility of uranium under these conditions, resulting in anomalous eU/eTh and eU/K ratio measurements, provides the best pointer to sites where mineralizing processes are most likely to have occurred.

Since uranium and thorium are lithophile elements, they can serve as pathfinders for a number of commodities including Li, Cs, Be, Nb, Ta, Zr, and rare earth elements which are concentrated in some types of pegmatite. The Winnipeg River area of Manitoba provides a good example of the application of airborne gamma-ray spectrometry to the discovery and classification of complex pegmatites and their parent granitoids on the basis of their distinctive radiometric signatures, which are most clearly demonstrated by a ternary colour map (*see Price et al.*, Paper 61, this volume; Geological Survey of Canada 1987).

Less common, but potentially of greater economic interest because of their much larger size, are peralkaline intrusions, such as in the Gardar Province of Greenland referred to above, Strange Lake, Labrador, and Thor Lake, Northwest Territories (Maurice and Charbonneau 1983). These contain a similar suite of elements to the complex pegmatites and are readily recognizable because of their very

high eU and/or eTh, with or without high K (*see* Plates 21.1 and 21.2). In addition to these peralkaline intrusions, a number of carbonatitic complexes have been discovered as a result of regional airborne gamma-ray spectrometry surveys (Heinrich 1966; Ford *et al.*, in press).

Late-stage leucocratic granites, which often exhibit Sn and/or W and sometimes Mo enrichment, with the possibility of economic mineralization, occur more commonly than peralkaline intrusives, and are often characterized by a less extreme but readily recognizable radiometric signature. High eU, with a high eU/eTh ratio, is usual, often accompanied by high K and some enrichment in Th, distributed in concentric or irregular zones.

The effectiveness of airborne gamma-ray spectrometry as an indicator of granophile element differentiation within a complex suite of granitic rocks in Nova Scotia has been documented by several authors (Chatterjee and Muecke 1982; Ford 1982; Ford and O'Reilly 1985; Slaney 1985; Ford and Carson 1986; Corey 1987). Plates 21.8a and 21.8b show the ternary and eU/eTh ratio maps for 1 km line spacing airborne gamma-ray spectrometry data over an area surrounding the East Kemptville tin deposit in southwestern Nova Scotia. Whilst the ternary map subdivides the Davis Lake Complex from the rest of the South Mountain Batholith, it is the eU/eTh ratio map which pinpoints the East Kemptville tin deposit.

The effectiveness of gamma-ray spectrometry for distinguishing Sn-W mineralized granitoids in Tasmania and New South Wales, Australia, corroborating the results obtained elsewhere, has been described by Webster (1984) and Yeates *et al.* (1982).

In contrast to granites, ultrabasic rocks are distinguishable by their almost total lack of radioelements. It should be noted that they are also normally characterized by an absence of magnetite, making them non-magnetic (*see* Plate 21.9a). Pure carbonates are the only rocks with which they could be confused geophysically. Ultrabasic rocks are of economic interest because they are potential sources of chromium and platinum group elements.

BASE METAL AND GOLD EXPLORATION

The above examples have linked economic mineralization with distinctive radiometric features, easily recognizable because they give rise to anomalies at the limits of the normal concentration range. They stand out even if radiometric data is examined in isolation from other geoscientific information. There are other circumstances where radiometric pointers to mineralization may be less obvious, because concentrations are within the range of values commonly encountered, but they are nevertheless anomalous for the lithology where they occur. These situations can only be recognized by correlating radiometric with geological and other geophysical/geochemical data. They depend upon the fact that many

mineralizing processes involve geochemical alteration which includes changes in the absolute and/or relative concentrations of the radioelements. This may consist of one or both of the following:

1. a marked change in K content
2. changes in one or more of the ratios

Clearly there must be a strong contrast with adjacent rocks, so what is recognizable in one environment might not be recognizable elsewhere.

Portnov (1987) has drawn attention to the significance of the K-Th relationship as an indicator of geological processes and a pointer to chalcophile as well as lithophile mineralization.

Gnojek and Prichystal (1985), described the use of airborne gamma-ray spectrometry to locate a zone of strong K alteration associated with Zn mineralization in Central Czechoslovakia. Potassium enrichment is accompanied by a decrease in Th, which they reported as typical of this type of secondary alteration. Potassium concentration increased by a factor of >2 and the eTh/K ratio by a factor of >4 over zones up to 1 km wide in the vicinity of mineralization. The greatest contrast, a ten-fold increase, was given by $K \times eU/eTh$ (Figure 21.3). Recognition of this enrichment was facilitated by the fact that K was introduced into spilites, a rock type with low potassium content.

Porphyry Cu deposits are often associated with K enrichment of the host rock. Moxham *et al.* (1965) were the first to demonstrate that gamma-

ray spectrometry could be used to detect and measure this alteration, and that an increase in K, which in the localities they studied averaged 1.5 percent K, was not accompanied by a corresponding increase in eTh. Thus, the eTh/K ratio is a good discriminator for this process in areas with a high K background. Moxham *et al.* (1965) reported that eU tended to increase erratically with increasing K. This reflects the greater mobility and therefore impermanence of eU under hydrothermal and supergene conditions, which, as later work cited in this paper has shown, is observable in many mineralized areas.

Gold is often thinly disseminated throughout porphyry copper deposits, and in those climatic regions where an oxidized cap has developed, is weakly concentrated in this upper part of the deposit (Boyle 1979). For the reasons given in the preceding paragraph, these alteration zones can be expected to be identifiable by airborne gamma-ray spectrometry. According to Boyle (1979), potassic alteration is common in many hypogene gold deposits, although the alteration zone is often narrow and may only involve redistribution of K. Carlin-type disseminated gold deposits are reported to show sufficient K enrichment to be measurable by gamma-ray spectrometry, increasing from 0.7 percent in unaltered unmineralized rock to an average of 1.6 percent where mineralized (Radtke *et al.* 1972). Some skarn-type gold occurrences have been discovered from ground follow-up investigations of radiometric anomalies revealed by regional airborne gamma-ray spectrometry surveys. The gold was found in specimen material characterized by its high eU and eU/eTh values (Charbonneau and Swettenham 1986). Ancient and modern gold-bearing placer deposits can often be pinpointed because the associated heavy minerals include radioactive species.

CONCLUSIONS

1. The airborne radiometric method is a powerful aid to geological mapping in regions where the geology is complex, or access is difficult. However, it must be noted that it is a surficial mapping method and it cannot provide information about underlying formations if their composition is not reflected in surface material.
2. This method can be applied in all climatic regions.
3. It is an effective method for recognizing localities where there are unusual rock types or where there has been strong alteration. These can be direct pointers to mineralization.
4. It is a particularly useful method for subdividing and exploring those extensive areas of unmapped granites and gneisses which exist in many parts of the world.
5. The method is most productive when used in conjunction with other airborne geophysical techniques, to minimize data acquisition costs and facilitate interpretation.

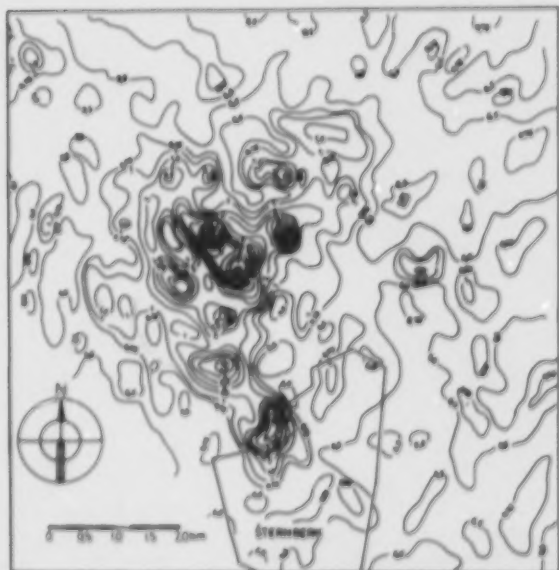


Figure 21.3. Map of the $K \times U/Th$ ratio values compiled from airborne data over a newly discovered buried zinc occurrence in Northern Moravia (Czechoslovakia) (from Gnojek and Prichystal 1985). Symbols show location of mineralized boreholes.

6. The interpretation process is best performed with the assistance of high-capacity, high-definition image processing systems, with on-line access to other geoscientific data.
7. Statistical techniques, for example, cluster analysis, allow maximum benefits to be obtained from quantitative data.
8. Regional compilations, based on controlled quantitative data, will contribute to a better understanding of crustal evolution.

ACKNOWLEDGMENTS

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22. Seismic Exploration in the Witwatersrand Basin, Republic of South Africa

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ABSTRACT

Auriferous conglomerates ("Reefs") of the Witwatersrand Supergroup have provided about 30 per cent of total world gold production. Geophysical exploration methods are mainly used for structural mapping of the host lithologies, rather than directly detecting the gold reefs.

The Anglo American Corporation of South Africa Limited mobilized the first Vibroseis crew to the Witwatersrand Basin in 1983 and commenced a seismic interpretation of the basin structure. Exploration successes over the past four years have established the Vibroseis method as the Gold Division's primary geophysical tool.

This paper discusses local Vibroseis data acquisition and processing parameters and presents three exploration case histories, commencing with an integrated geophysical study on the western Witwatersrand Basin margin. The advantages of the reflection seismic method over gravity interpretation techniques are emphasized.

The second case history relates to a more detailed 2D seismic survey conducted adjacent to an operating gold mine. The section selected for discussion clearly illustrates the seismic stratigraphy of the Witwatersrand and Ventersdorp Supergroups. This survey identified a potential extension to the ore reserves of the mine.

The final study is concerned with structural mapping within the deep basin. This Vibroseis survey delineated a horst block which elevates favourable conglomerates by 3000 m, bringing them within mineable depth limits.

INTRODUCTION

The Witwatersrand (Wits) Basin is located in the centre of the Kaapvaal Craton in the Republic of South Africa (Figure 22.1). It is an early Archean, circa 2700 to 3100 Ma, sedimentary basin of some 50 000 km² containing 7 km of the argillaceous and arenaceous Witwatersrand Supergroup overlain by a further 7 km of volcanics, sediments, and intrusive sequences of the Ventersdorp and Transvaal Supergroups (Figure 22.2).



Figure 22.1. Regional location, surface, and subsurface geology of the Witwatersrand Basin (after Pretorius 1986, with modifications).

Most of the gold mined from the basin is contained in auriferous paleoplacer conglomerates (termed "Reefs") in the 2.5 km thick Central Rand Group (age 2800 Ma). Since 1886, 150 gold mines have yielded some 40 000 t of gold and 120 000 t of U₃O₈ at average grades of 10 g/t and 0.23 kg/t, respectively. Mining has exploited the reefs at an average dip of 20° to depths of 4000 m and currently

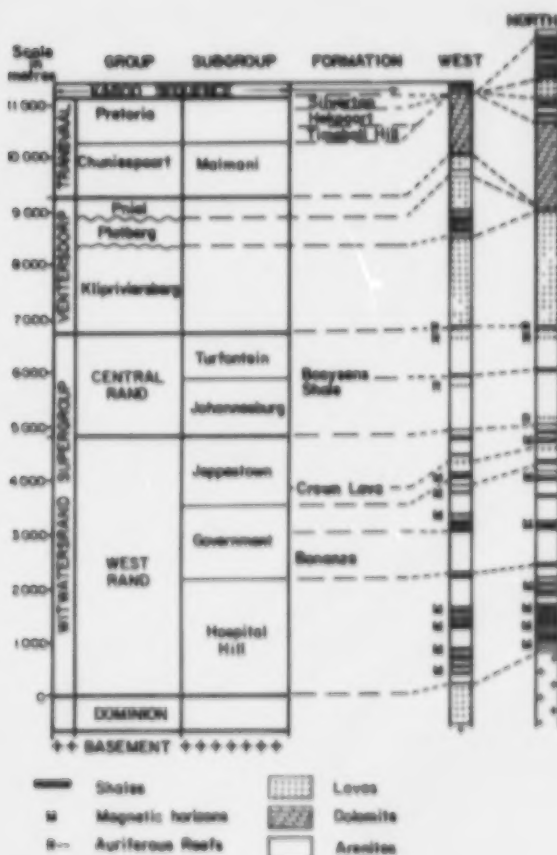


Figure 23.2. Lithostratigraphic columns in the Witwatersrand Basin.

45 mines are producing 685 000 kg of gold per annum (Pretorius 1974, 1986).

With increased thickness of cover rocks and largely unknown structures, exploration became reliant upon gravity and magnetic methods to define drill targets. These methods led to the discovery of several new goldfields and extensions to mined areas in the period 1930 to 1950 (Roux 1967; Krahmann 1936).

In the 1970s, Anglo American Corporation recognized that the seismic reflection method could be a valuable technique for resolving the structure and stratigraphy of the Witwatersrand Basin. Practical investigation commenced in 1981 with Vertical Seismic Profiling (VSP) surveys in numerous exploration drillholes. This was followed by negotiations with government departments and Vibroseis survey trials which culminated in the decision in 1983 to launch the first major seismic reflection survey in the Witwatersrand.

This program, employing a "dedicated" acquisition and processing crew, has met with considerable

success over the last four years. As with gravity and magnetics, the seismic reflection method has mainly been employed for structural mapping of the host lithologies, rather than directly detecting the Gold Reefs. It has led to a more comprehensive understanding of the Basin structure on which to base the selection of drilling targets and planning of exploration.

This paper provides a brief overview of Witwatersrand stratigraphy and discusses local Vibroseis data acquisition and processing parameters. Three interpretation case histories are then presented to illustrate typical applications of the seismic method in the gold exploration program. These include a discussion of geophysical well-logs and an example of integrated interpretation of seismic and gravity data.

GEOLOGICAL OVERVIEW

The Witwatersrand (Wits) Basin lies in the centre of the Archean Kaapvaal Craton of Southern Africa. After consolidation of this Craton circa 3100 Ma, the Wits Basin formed as the second in a series of volcano-sedimentary basins on the crustal platform. It contains an infill which is collectively referred to as the Witwatersrand Triad, comprising the Dominion group of basal sediments and differentiated volcanics; the Witwatersrand Supergroup, and the Ventersdorp Supergroup.

The Witwatersrand Supergroup is exposed on portions of the northern and western basin periphery, and as a collar around the Vredefort dome structure (Figure 22.1). It dips inwards at an average of 20° and is sequentially covered by the rocks of the Ventersdorp and Transvaal Supergroups. Major intrusives such as the Bushveld Complex and the Vredefort Dome cryptoexplosive event occurred at around 1900 Ma. The basin was finally covered by Karoo strata which are preserved over the southern and eastern half of the craton.

The gold deposits formed on laterally extensive unconformity surfaces, as stratigraphically separate paleoplacers. These are considered to be alluvial fan deposits which have been reworked as basin wide braided stream placers. Extensive mining has revealed the size and shape of individual fans, together with their channel distribution and preserved sedimentary facies. The areas within the basin where mineralization is economically concentrated can be grouped into eight goldfields (Figure 22.1).

The stratigraphic column (Figure 22.2), demonstrates the marked vertical change in the lithologies. The argillaceous West Rand Group transitionally changes upwards into the arenaceous Central Rand Group which contains the auriferous conglomerates. Argillaceous and volcanic marker units (Booyens Shale and Crown Lava) facilitated regional stratigraphic correlation and contributed to the success of seismic reflection applications.

GEOPHYSICAL WELL-LOGGING

Tests preceding the Vibroseis survey included a major Vertical Seismic Profiling (VSP) program during 1981 and 1982. It was felt that the VSP surveys would provide a more practical evaluation of the reflectivity of Witwatersrand Triad rocks than earlier synthetic seismogram studies. A total of 24 drillholes were logged which covered a broad range of stratigraphy in proposed seismic survey areas. The VSP results indicated that a surface seismic survey would succeed in mapping many of the horizons of interest and, on the strength of this, the first Vibroseis crew was mobilized to the Witwatersrand.

The reflectivity and velocity information gathered during this first program played a valuable role in the interpretation of the early seismic sections and provided the impetus for an ongoing geophysical well-logging program. Some of the results are summarized in Table 22.1.

Since the initial program, there has been a considerable expansion in the Corporation's geophysical well-logging activities. A substantial portion of the annual budget is allocated for logging of exploration drillholes sited adjacent to existing or future seismic lines. In proposed survey areas where there is no current drilling activity, old boreholes may be specifically reopened for geophysical logging. The range of logs has expanded to include VSP, acoustic, density, natural gamma, resistivity, caliper, gyroscopic, and temperature surveys. Some of the geophysical well-logging results will be discussed in conjunction with the relevant seismic case histories.

DATA ACQUISITION

SCOPE OF OPERATIONS

The Corporation's Vibroseis surveys may be broadly divided into three categories:

TABLE 22.1. TYPICAL P WAVE VELOCITIES AND REFLECTION COEFFICIENTS FOR THE WITWATERSRAND BASIN.

Group/Formation	P wave average Interval Velocity (m/s)	Approximate * Reflection Coefficients
Karoo Sequence	3195	+0.336
Hekpoort Formation (Acid Lavas)	6083	
		-0.068
Timeball Hill Formation (Shales)	5513	+0.143
Malmesbury Subgroup (Dolomites)	6834	-0.061
Pniel Group (Basic Lavas)	6159	-0.028
Platberg Group (Sediments)	5827	+0.033
Klipspruit Group (Basic Lavas)	6230	-0.065
Central Rand Group (Quartzites)	5779	+0.025
West Rand Group (Quartzites and Shales)	5748	-0.032
Basement Granite	5695	

* Density Data Incorporated From Geophysical Well-Logs

1. reconnaissance 2D surveys making use of the public road network and concentrating on the gaps between the goldfields close to the basin margin (where the targets are generally shallower)
2. reconnaissance 2D surveys over the deeper portions of the basin, aimed at delineating structural highs which could elevate gold-bearing strata to mineable depths (i.e. 4000 m below surface)
3. detailed 2D surveys conducted over and adjacent to mine properties with a view to mapping structure and investigating possible extensions to ore reserves

One case history from each of these categories will be discussed under the heading "Interpretation Case Histories."

ACQUISITION EQUIPMENT

Details of acquisition equipment appear in Table 22.2. A change from the original Sercel SN 338 recording equipment to a Sercel SN 368 Telemetric system with a CS 2502 field correlator-stacker took place in early 1987.

ACQUISITION PARAMETERS

Typical acquisition parameters for reconnaissance Vibroseis surveys are presented in Table 22.2. Factors involved in the choice of selected parameters are discussed below, with reference to this table.

1. Fold of Stack

Nominally set at 48, the fold of stack has been varied from 24 to 60 fold, depending on the signal-to-noise ratio and structural complexity in different target areas.

2. Station Interval

The main factors considered in selecting the station interval are the prevention of spatial aliasing and sampling requirements for migration of the seismic sections. A station interval of 50 m is generally used where the subsurface structure is poorly known. This allows for the migration of frequencies up to 45 Hz without dispersion for dips of up to 45°, assuming that $V_{rms} = 6000$ m/s (a reasonable figure for the Wits Basin). The station interval may be reduced in follow-up surveys, when the data frequencies and dips are better known.

3. Geophone and Vibrator Patterns

These vary from area to area, and are selected on the basis of noise analyses, computer simulation of

TABLE 22.2. VIBROSEIS RECORDING EQUIPMENT AND ACQUISITION PARAMETERS.

i) Recording Equipment	
Vibrators:	5 x Felling B.B.V. Vibrators complete with Pelton Vibrator Electronics including programmable variable and non-linear sweep options.
Recording System:	
i) 1983-1986	90 Channel Sercel SN 338 recording system.
ii) 1987	120 Channel Sercel SN 368 Telemetric Recording system, 4 milliseconds sampling, complete with CS 2502 Correlator Stacker (120 traces, 4 milliseconds) and digital sweep generator.
Geophones:	Sensor SM-4 10 Hz Geophones.
ii) Typical Acquisition Parameters	
Fold of Stack	48
Station Interval	50 m
Geophone weighting and pattern	111123222321111 centred on peg, element spacing 7.5 m.
Geophones per trace	24
Vibrator pattern	11111222112221122211111 four vibrators in line-ahead, 33 m spacing, centred between pegs, 7 m move-ups.
Sweeps per trace	8
Sweep	10 - 90 Hz
Sweep length	26 seconds
Listening time	8 seconds
Spread	2525 m-175 m-0-175 m-2525 m

array responses and production testing. The patterns shown in Table 22.2 are logistically easy to lay and perform reasonably well in attenuating the main refractors and airwave. High velocity refractors in the Wits Basin are attenuated by using long source and receiver patterns. These refractors can also be combated by omitting frequencies in the 10 to 24 Hz range from the sweep (the dominant refractor frequency is 20 Hz). However, this measure also leads to the deterioration of the deeper reflection data and is only taken if refractor noise occupies a large portion of the dynamic range of the instruments. Figure 22.3 shows a typical noise analysis, illustrating the effectiveness of the convolved array response.

4. Sweeps per Trace

This parameter varies around the basin, depending on ambient noise conditions. A value of eight was the figure used in the case histories below.

5. Sweep

The following factors are taken into consideration when choosing a sweep for each new prospect:

1. reduction in surface-wave amplitude, the airwave and refracted energy; (discussed under 3 above)
2. reduction in correlation noise and prevention of harmonic ghosting
3. optimizing the depth of penetration (signal-to-noise ratio) and resolution

Several sweeps may be tested during noise analyses and production trials preceding the survey.

Combi-sweeps and non-linear sweeps have been employed for high resolution surveys on some prospects.

6. Spread

In areas where little is known of the subsurface structure, a symmetrical straddle spread is chosen

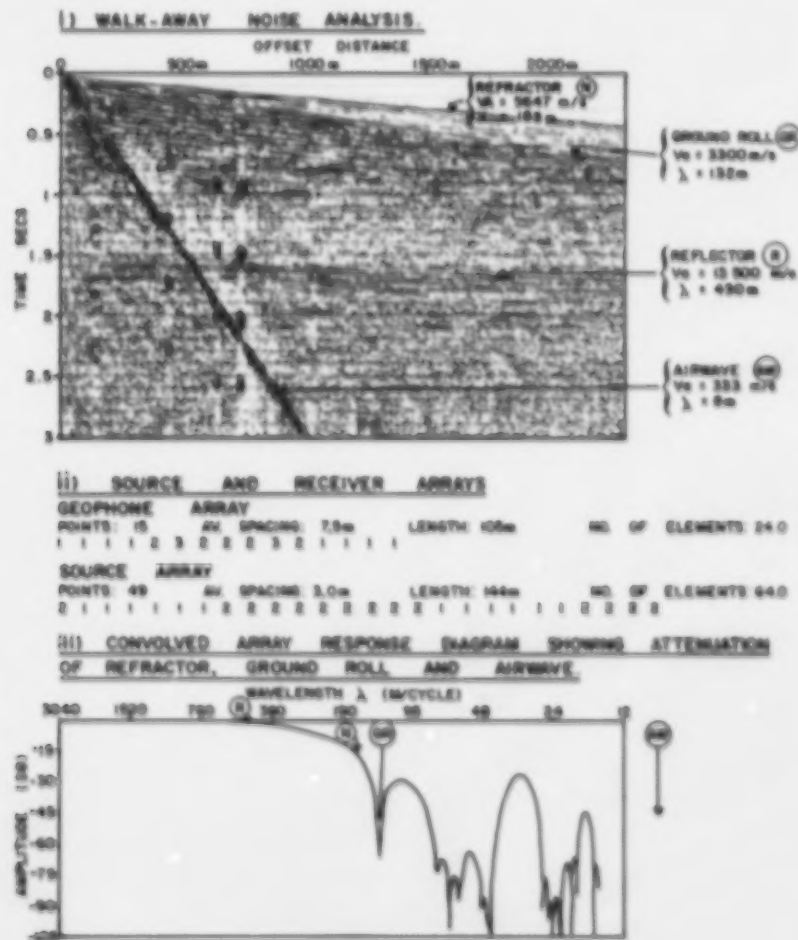


Figure 22.3. Noise analysis and design of source and receiver arrays.

with the parameters shown in Table 22.2. Once dips have been established, follow-up surveys may employ an end-on configuration, shooting up-dip into the spread.

The near-trace offset of 175 m allows reasonable sampling and coverage of shallow reflectors while avoiding high amplitude noise from the vibrators. Pertinent factors in selecting a far offset of 2525 m are:

- This offset minimizes data loss in the near-surface due to the stretch mute in processing.
- It allows for reasonable attenuation of multiples (if present) and converted waves during NMO (Normal Moveout) correction and stack. (Multiples are not usually a problem on most sections. Reasons for this will be discussed below).
- Velocity analyses, resolution and fold of stack are improved in the first two seconds of data (i.e. 0 to 6000 m depth) which is the main interval of interest.

DATA PROCESSING

PROCESSING FACILITIES

The Corporation commissioned it's own local processing centre at the beginning of the survey program. This has paid handsome dividends in terms of encouraging frequent interaction between processing and interpretation staff, resulting in refinement of the processing route and better quality sections. The processing centre employs a Vax 11/780 computer. In addition to seismic data processing, this machine is used to maintain a comprehensive geological and geophysical data base for all survey areas.

PROCESSING ROUTE

A generalized processing flowchart is presented in Figure 22.4. This may be varied from area to area dependent on survey objectives. An important point to note about this route is the surface consistent application of processes such as Deconvolution, F-K filtering, and residual static corrections. Emphasis on the surface-consistent aspect has led to considerable improvement in general section quality, completely justifying the longer processing times required for this complex route. Processing times are greatly increased if iterative surface-consistent deconvolution is undertaken, as has been the case on some high-resolution surveys. Certain aspects of the processing route will now be briefly discussed with reference to Figure 22.4.

1. Cross-Correlation

With the recent incorporation of the Sercel CS 2502 correlator-stacker in the data acquisition system, cross-correlation now takes place in the field.

TYPICAL DATA PROCESSING ROUTE



Figure 22.4. Typical data processing route.

2. Statics Application

Static corrections are calculated from the Vibroseis records employing a modified Gardner (1939) method calibrated against low velocity layer (LVL) derived statics at appropriate intervals. Note that the application of these field statics precedes F-K filtering, allowing for better definition of the apparent velocities of the signal in the F-K plane (see 3 below).

3. FK Filter

Although F-K filtering has always been an integral part of the processing route, there have been many changes in emphasis in its application. Basically, the F-K filter is used as a velocity filter set to protect the signal and attenuate noise. Fan-shaped filters are favoured as these optimize the attenuation of both random noise and low-velocity coherent noise (e.g. ground-roll). Occasionally, the filter may be used to attenuate refractors, but these have generally higher apparent velocities and care must be taken not to damage the signal. This is particularly important at

longer offsets on the down-dip side of the spread, where the apparent velocities of the signal may be as low as those of the refractors.

As a rule of thumb, a conservative cut-off velocity (V_c -max) is chosen which represents the apparent signal velocity of the shallowest event of interest at its largest anticipated dip and maximum stackable offset. The actual V_c is always kept lower than this value and gentle filter tapers are applied.

Figure 22.5 illustrates a typical F-K filtering exercise.

4. Source and Receiver Domain Sorting

The requirement for source and receiver domain sorting between passes of deconvolution and F-K filtering greatly increases the processing time per record in a surface-consistent route.

5. Deconvolution

The advantages of surface-consistent deconvolution and its application in the Witwatersrand Basin are based on many years of research, adaptation, and refinement, a full discussion of which is beyond the scope of this paper.

6. Normal Moveout (NMO) Correction

Interval velocities provide the major discriminating factor when comparing the seismic response of the Witwatersrand 'hard' rock environment with the

'soft' rock sedimentary environments normally encountered in oil exploration.

Average pre-Karoo interval velocities for rocks in the Witwatersrand Basin are 6000 m/s (Table 22.1), compared with ± 2500 m/s in 'soft' rock sedimentary basins.

Reflection coefficients, with the exception of the base Karoo, are generally low by comparison to 'soft' rock sedimentary basins (Table 22.1).

These facts have two notable effects on seismic reflection data quality:

1. The amplitude ratio between primary and multiple reflections is relatively high by comparison with 'soft' rock environments. This results in low amplitude and generally unobservable multiples. This is particularly fortuitous since multiple attenuation using traditional techniques employing differential NMO would not be applicable in this situation.
2. The extremely high interval velocities, and therefore extremely small NMO, enable relatively large errors in the stacking velocities with a minimal effect on the coherency of the reflections. This is particularly useful when stacking highly variable cross dips in the same spatial position.

With these points in mind, the first stage in the determination of velocities for NMO is the production of a 'Rawstack' using an RMS stacking velocity of 6000 m/s for the entire section. Analysis panels are selected at appropriate intervals on this stack

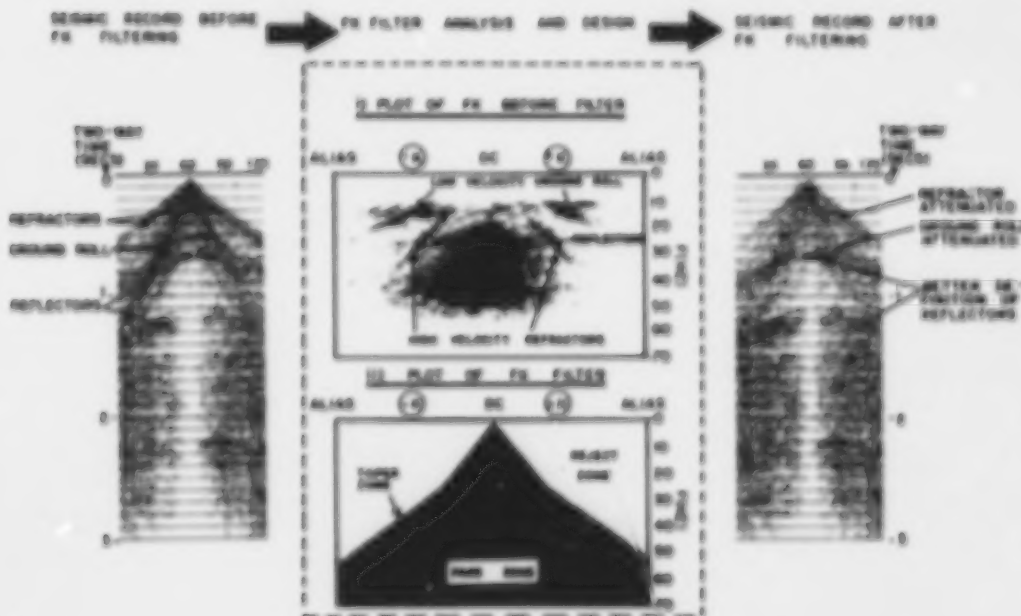


Figure 22.5. F-K filtering exercise in an area with high velocity refractors.

and detailed NMO functions are derived using constant velocity stacks and gathers. Rather than relying on automatic NMO muting criteria, the project seismologist interactively selects time and space variant mute functions. Iterative velocity and static analyses have proven very beneficial on some sections.

7. Migration

Following the surface-consistent residual statics application, the final stack is migrated using a steep dip two-dimensional migration algorithm. Migrated velocity fields are supplied by the interpreters and are usually based on a preliminary interpretation of the final stack. Pre-stack migration has also been undertaken in areas of steep dip.

INTERPRETATION CASE HISTORIES

CASE HISTORY 1. SEISMIC INVESTIGATION OF THE WESTERN BASIN MARGIN

The first case history to be discussed is a seismic section over the Western Basin Margin which is particularly representative of the seismic stratigraphy in this part of the basin. It also illustrates the ambiguity of gravity interpretation methods in the absence of stratigraphic control.

The interpreted time section is presented in Figure 22.6a and the depth-converted interpretation in Figure 22.6b. Panel ABCD on Figure 22.6a has been enlarged for greater clarity in the discussion of seismic stratigraphy (Figure 22.7). While discussing this interpretation reference will be made to local geophysical well-logging results, an example of which is presented in Figure 22.8.

The following horizons have been interpreted on this section.

Base of Silverton Formation

The contact between the Silverton Shales, and underlying Hekpoort Andesite is an acoustic impedance increase. The resulting positive reflection coefficient is represented by a trough (white peak) on these SEG1 polarity displays. Note the strong, laterally continuous reflections on Figure 22.7 which are typical of the Silverton Shales.

Base of Hekpoort Formation

By contrast with the Silverton Shales the Hekpoort Andesites have few internal reflections. The decrease in velocity from the andesites to the underlying Timeball Hill Sediments generates a negative reflection coefficient Black peak on SEG1 displays (Table 22.1).

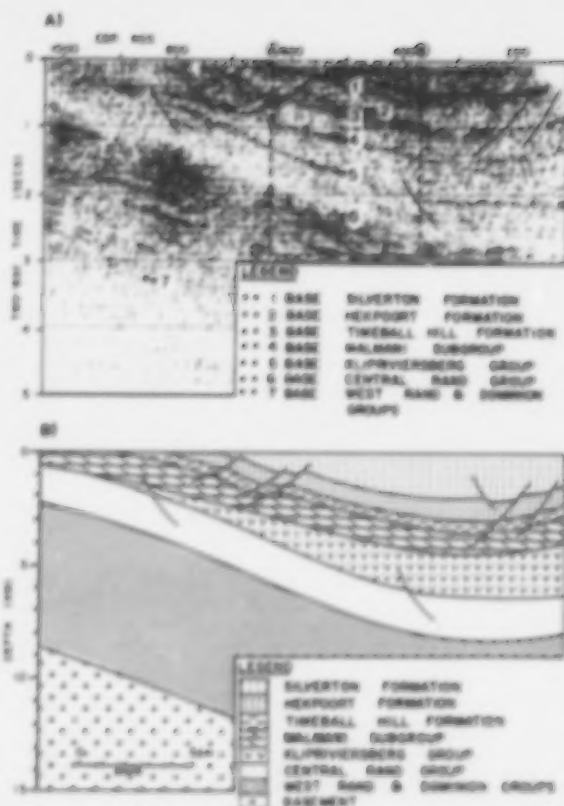


Figure 22.6. a) Interpretation of seismic section 1; b) Depth-converted interpretation of seismic section 1.

Base of Timeball Hill Formation (Base Pretoria Group)

There is a distinct difference between the internal reflection character of the Timeball Hill Shales (high amplitude, laterally continuous reflectors) and that of the underlying Malmari Dolomites (lower amplitude reflectors with less continuity). A positive reflection coefficient (trough) occurs at the contact between the slower velocity shales and the fast dolomites.

Base Malmari Subgroup

A high amplitude black peak (negative reflection coefficient) is developed at the contact between the Transvaal Dolomites and the underlying Black Reef Quartzite. This is clear on Figures 22.7 and 22.8. This is one of the main marker horizons in the Wit Basin.

Base Klipriviersberg Group

Although the Klipriviersberg Lavas and Central Rand Group Quartzites have a similar internal re-

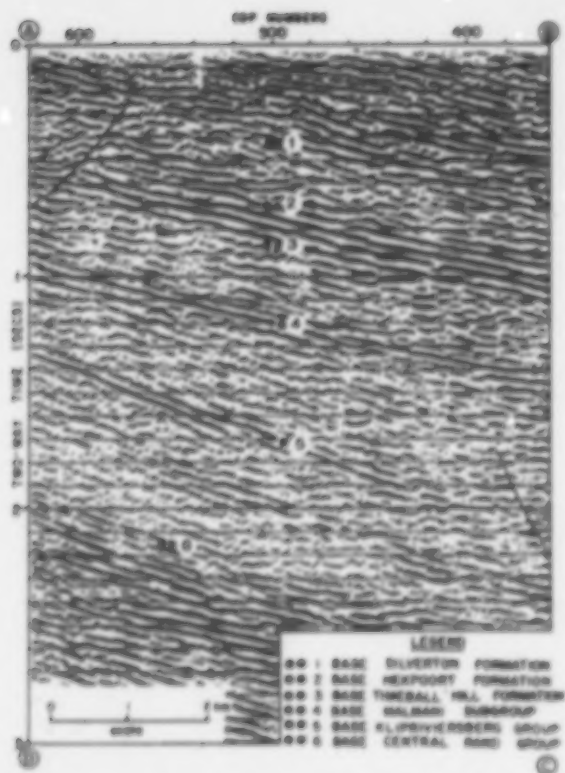


Figure 22.7. Enlargement of panel ABCD on seismic section 1.

flection character, the decrease in P wave velocity from 6300 m/s in the lavas to 5900 m/s in the quartzites provides a strong black reflector (Figures 22.7 and 22.8). This is a particularly important horizon as it defines the top of the prospective Central Rand Group Rocks. In areas where the Ventersdorp Contact Reef (VCR) is developed, this can be directly mapped from the sections.

Base Central Rand Group

The mainly arenaceous Central Rand Group is characterized by an absence of internal reflectors with lateral continuity. By contrast, the predominantly argillaceous West Rand Group is characterized by a large number of parallel reflections, representing the contacts between alternating layers of quartzite and shale (Figures 22.6a and 22.7). The contact between the Central Rand Group and the underlying West Rand Group is chosen at the onset of the strong reflections.

Base West Rand and Dominion Groups (Top of Basement)

This is chosen at the base of the zone of strong, laterally continuous reflections (Figure 22.6a).

Gravity Modeling Exercises

Prior to the seismic survey, gravity modeling exercises in the area had indicated the presence of major horsts, which could elevate Central Rand Group Rocks to mineable depths in the deep basin. Figure 22.9a illustrates one of these modeling studies. A relatively shallow block (A) of low density Central Rand Group quartzites was proposed to explain the subtle gravity low GL1. Note that although block A

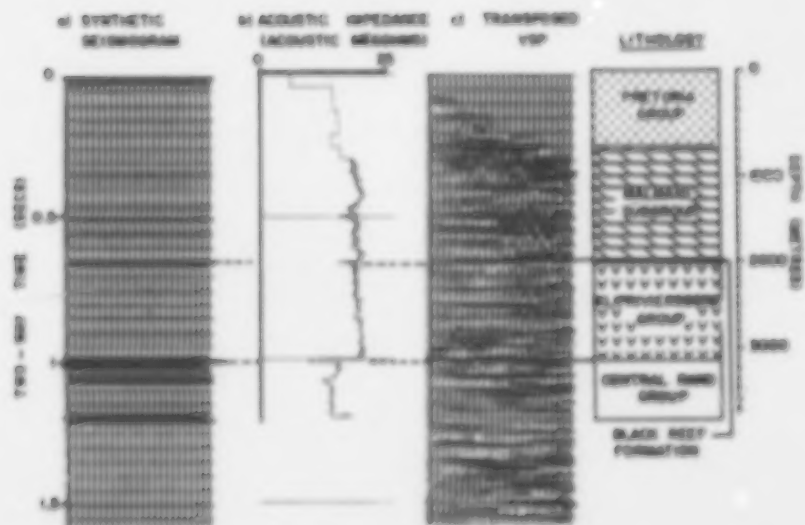


Figure 22.8. Geophysical well-logs from the West Wit Area.

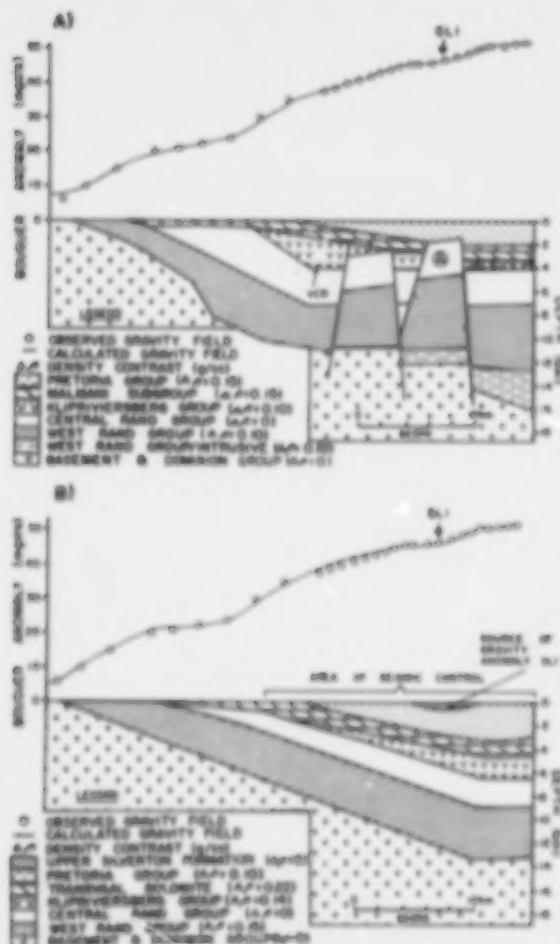


Figure 22.9. a) Early gravity modeling exercise without seismic control; b) Gravity modeling exercise with seismic control.

is upthrown by 3000 m, this structure only generates a residual gravity anomaly of 3 milligals, superimposed on the strong regional gradient. Another point worth mentioning here is that the interpreter has thickened the dense West Rand Group and invoked a possible intrusive to explain the regional gradient. This has allowed him to flatten the dips on the younger formations and maintain a depth to Ventersdorp Contact Reef (VCR) of less than 4200 m along the entire section. This is all within current economic exploration limits.

With the benefit of stratigraphic control provided by Figure 22.6a and other seismic sections in the area, it appears that gravity lows such as GL1 are actually caused by low density Pretoria Sediments close to the surface. This is illustrated by the gravity model in Figure 22.9b, which employs density contrasts derived from local geophysical well-logs. This model also indicates that the West Rand Group

maintains a constant thickness into the basin and that the Transvaal and Ventersdorp Group Rocks must be thickened to explain the strong regional gravity gradient. The VCR thus rapidly reaches depths in excess of 5000 m on the section and this is beyond economic exploration limits.

This modeling exercise clearly illustrates the ambiguity of traditional gravity interpretation methods in deep basin search. Modeling of the regional gravity field forms an important part of such interpretation exercises and this requires the type of stratigraphic control which can only be provided by the reflection seismic method. Integrated gravity and seismic interpretation has led to considerable modification of exploration drilling programs in this and other target areas.

CASE HISTORY 2. DETAILED SEISMIC SURVEY ADJACENT TO MINE LEASE AREA

The second case history briefly outlines a detailed 2D seismic interpretation adjacent to an existing gold mine. The survey was commissioned primarily to delineate the structure of the strata, and define those areas where the relevant horizons are shallow enough for future mining.

The area covered by the survey amounts to approximately 500 km², and a total of 180 line km were recorded. The distance between adjacent lines varied between 2 and 8 km.

The data quality in this area proved to be excellent, and the data acquired became 'TYPE' sections for the seismic character of many of the geological formations in the Witwatersrand Basin.

A depth converted interpretation, together with the original seismic section and an enlargement are presented to illustrate the salient features for this review (Figures 22.10a, 22.10b, 22.11).

The relevant horizons and seismic character are described below.

Dase Pniel Group

Nearby borehole and VSP logs indicate the contact between the Upper Ventersdorp lavas and the underlying Kameeldoon sediments to be an acoustic impedance decrease. This is represented seismically by a black peak on these SEG1 polarity displays (Figures 22.10a and 22.11). In addition to this, the boundary can be identified by the dramatic change in seismic character from the weak, intermittent, parallel reflections within the Upper Ventersdorp Lavas to the strong, high amplitude reflections of the Platberg sediments.

Base Platberg Group

The sediments of the Platberg Group lie unconformably on the Klipriviersberg Lavas. The unconformity is extremely well illustrated on section 2 (Figures 22.10a and 22.11) as an angular unconformity

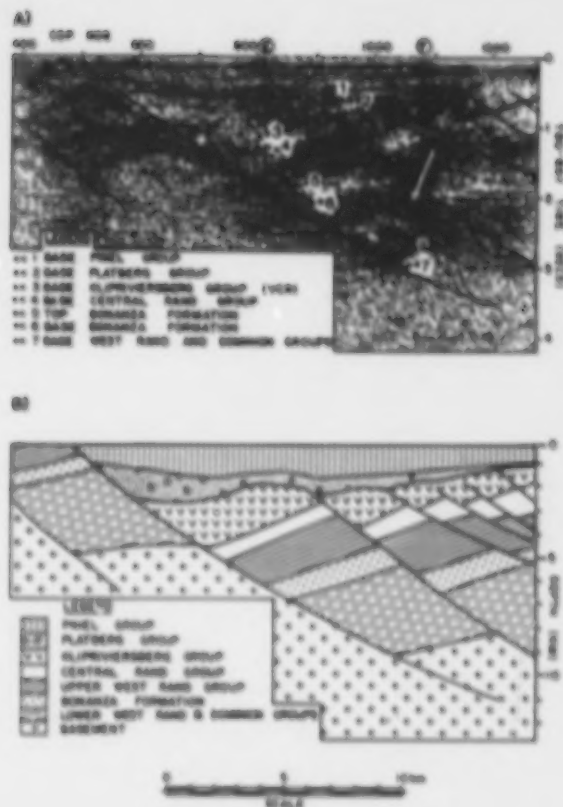


Figure 22.10. a) Interpretation of seismic section 2; b) Depth-converted interpretation of seismic section 2.

of up to 25°. This marks a change in seismic character from the generally strong reflections of the Platberg sediments to the weaker, parallel reflections which characterize the Klipriviersberg Lavas.

Base Klipriviersberg Group (Ventersdorp Supergroup)

As outlined in the first case history, and confirmed by numerous velocity and VSP logs, the contact between the Klipriviersberg Lavas and the Central Rand Group Quartzites constitutes a decrease in acoustic impedance, represented seismically by a black peak on SEG1 Polarity displays (Figure 22.11).

The contact is also identified by the change in seismic character from the relatively strong, parallel reflections of the Klipriviersberg Lavas to the very weak, intermittent reflections of the Central Rand Group Quartzites.

Geologically, this horizon coincides with the 'Ventersdorp Contact Reef' or VCR. Using seismic reflection methods, this horizon can be accurately mapped throughout the basin.



Figure 22.11. Enlargement of panel EFGH on seismic section 2.

Base of Central Rand Group

As in case history 1, the base of the Central Rand Group Quartzites is chosen at the onset of the strong reflections which mark the beginning of the argillaceous Jeppestown Subgroup at the top of the West Rand Group.

Bonanza Formation

Worthy of particular mention in this area, is the excellent seismic representation of the quartzitic, reef-bearing Bonanza Formation (Figure 22.11). This consists of weak, intermittent reflections, similar to the Central Rand Group, but overlain and underlain by the strong, near parallel reflections which characterize the remainder of the West Rand Group.

Fault Plane Reflection

Figure 22.11 displays an excellently defined fault plane reflection. This further illustrates the extremely good data quality in this area.

Structural Mapping

The depth maps resulting from this interpretation define the major faults and their trends, the strike

and dip of the strata, and the depths to the relevant reef horizons. The accuracy of the interpretation has been confirmed by several recent boreholes sited on seismic targets.

Fault 11f1' elevates the Central Rand Group by 2300 m to the west of CDP 980 (Figure 22.11). This is an excellent example of the primary purpose of this survey. Previous geological interpretations had failed to predict this block, which is shallow enough for future mining considerations.

CASE HISTORY 3. SEISMIC STRUCTURAL MAPPING WITHIN THE BASIN

Parts of two seismic sections are presented which tie at a junction above a significant structural uplift in the central part of the Witwatersrand Basin (Figure 22.12). The two sections are part of a regional in-basin reconnaissance survey. They illustrate the power of the seismic method in determining areas of structural uplift when accompanied by seismic definition of Witwatersrand stratigraphy. The lines are tied as one composite section forming an obtuse angle of 145° from west to southeast.

Individual horizons and seismic character are similar to Case History 1, with the addition of Karoo

cover which is too shallow for delineation by the acquisition geometry of the survey. The Pniel Group lavas are also present and rest unconformably upon the Klipriviersberg and Central Rand Groups. This unconformity is defined beneath the Malmesbury by a weak, intermittent reflection above the Klipriviersberg Lavas which sharpens into a strong event where it truncates a structural horst of Central Rand Group strata (CDP's 2240 - 1240). Case history 2 discusses the Pniel and Platberg Groups of the Upper Ventersdorp in more detail.

The sections show the dramatic nature of the Pniel unconformity, with the gently warped strata of the Upper Ventersdorp, Transvaal, and Karoo lying above it and the sharply faulted horst block beneath it. The horst uplifts the Central Rand Group quartzites by 3000 to 5000 m giving a target into the Central Rand Group at a depth of less than 3000 m.

On section 3, the base of the Klipriviersberg Group is interpreted as the strong black peak dipping eastward toward the horst below 1 second (CDP's 2000 - 2160 - Figure 22.12). On section 4, this horizon dips westward towards the horst (CDP's 1350 - 1620, 1.5 - 2 seconds). The horst is most clearly demonstrated on the sections where the strong parallel reflections of the West Rand Group are faulted against the intermittent, subparallel, sparse reflections of the Klipriviersberg and Central Rand Groups.

The seismic section successfully revealed deeply buried and hidden major structures within the deepest part of the Witwatersrand Basin. This was accomplished with sufficient stratigraphic resolution to indicate a target for exploration. A borehole, sited on this target, drilled and accurately confirmed the stratigraphy and structure indicated by the seismic interpretation, the results of which are summarized in Figure 22.13.

CONCLUSIONS

The reflection seismic method has been successfully employed for structural mapping within the Witwatersrand Basin, despite the relatively small reflection coefficients in this hard rock environment. In the search for new ore reserves, attention is being focused on the deeper portions of the basin where traditional gravity and magnetic interpretation techniques lack the resolution required for accurate identification of drill targets. Greater reliance will therefore be placed on the Vibroseis method in future gold exploration programs.

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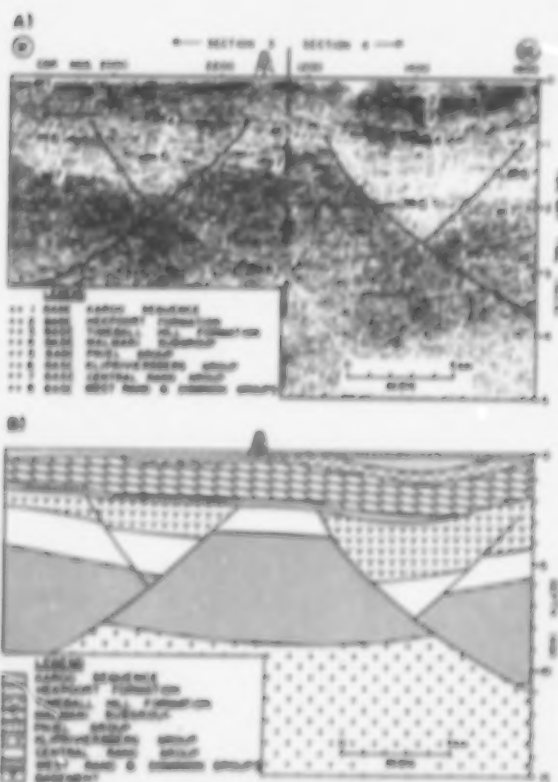


Figure 22.12. a) Interpretation of seismic sections 3 and 4; b) Depth-converted interpretation of seismic sections 3 and 4.

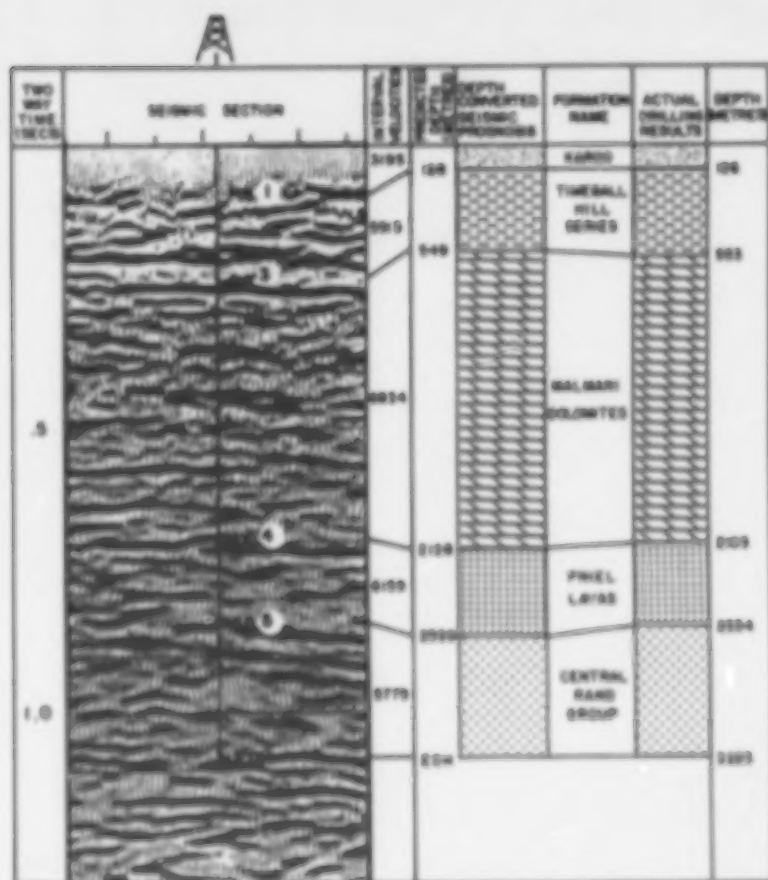


Figure 12.13. Borehole prognosis on seismic section 3.

pecting Services (AAPS), Exploration Consultants Limited (ECL), and Rockplan for their suggestions and comments during the preparation of the manuscript.

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23. Geophysical Mapping of Precambrian Granite-Greenstone Terranes as an Aid to Exploration

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ABSTRACT

In many of the world's Precambrian shield areas, particularly where subdued topography and either deep weathering or surficial cover reduces bedrock exposure to a minimum, extensive regional geophysical surveys have been carried out with the aim of producing new information about the hidden geology. The results of regional gravity, aeromagnetic and, to a lesser extent, gamma-ray spectrometer surveys now have an established role as fundamental geo-data sets. Particularly in the case of aeromagnetic data, the surveys reveal a complex pattern of anomalies, loosely described as magnetic signatures or thumbprints. These are often clearly different from one geological province to another, and from one suite of rocks to another within a given province.

As with the Canadian Shield, these geophysical maps are often readily available for the benefit of all potential users. However, the systematic interpretation of the data they contain appears relatively neglected, partly in practice and more seriously in the literature of geophysical methodology.

In mineral exploration, an important practical objective of interpretation is often the differentiation between the mineral-rich volcano-sedimentary greenstone assemblages of low metamorphic grade and the larger areas of relatively barren high-grade granite-gneiss. The aim in economic terms is the selection of limited areas of greatest economic potential for more intensive exploration, i.e. "area selection".

An attempt is made in this paper to draw on the fund of published and unpublished experience gained in the interpretation of regional geophysical maps over Precambrian terranes in Canada, Africa, India, Asia, and Australia through the presentation of examples of geophysical anomalies and signatures and their interpretations. This inevitably requires attention to the distribution of magnetite in Precambrian terranes and its relationship to the conceptual models of mineralization processes central to exploration strategies.

INTRODUCTION

The last ten years have seen the continued accumulation of regional geophysical data at a high rate over large areas of the world. For aeromagnetic surveys, a steady rate of about two million line-kilometres per

year has been sustained for over 20 years (Reford 1980); annual statistics reported by the Society of Exploration Geophysicists show that this has continued up to the present time. Few large land areas remain totally untouched by gravimeter surveys, and although somewhat more confined in application so far, regional gamma-ray spectrometer surveys are certainly joining the ranks of accepted and essential geo-data sets (Darnley and Grasty, Paper 21, this volume). The gravity and magnetic survey coverage of the continents and their continental shelves is still far from complete, but existing data already provides a) general completeness at a sub-continental scale for many large areas, and b) considerable detail in selected local areas.

For the explorationist, the value of these data sets lies in the ability of the geophysicist to interpret them in meaningful geological terms and for the resulting new perception of the geology to lead in turn to new opportunities for discovering economic mineralization (Paterson and Reeves 1985). The objective of this paper is to illustrate some of the ways in which the first stage of this process has been achieved in several different parts of the world, and the contribution that this has made to the understanding of subcontinental scale geological structure and tectonics, particularly with regard to the Precambrian.

The effectiveness of both gravity and magnetic data sets in this regard stems from the following: a) the thin surficial cover which obscures the Precambrian geology from direct observation in many large continental areas (e.g. glacial till, desert sands, deep tropical weathering, lakes and shallow seas) is effectively "transparent", allowing survey data to be interpreted in terms of the disposition, structure and lithology of the underlying bedrock; b) with or without superficial cover, deep-seated structures and rock units at depth within the crust may be interpreted both qualitatively and quantitatively; and c) the extent in depth of outcropping geological units may be estimated.

The increasing realization of the importance of these capabilities is evident not only in the ongoing drive to acquire new data, but in efforts to compile all data into maps of continental scale which give new insight into major tectonic structures only partially revealed by localized surveys. Canada, through the Geological Survey of Canada and the Earth Physics Branch which is now incorporated, has traditionally taken the lead in publishing (and periodi-



Figure 23.1. a) Estimated aeromagnetic coverage of Africa from personal knowledge of numerous contributors (1987). Stippled areas: known survey areas. Estimated percent coverage given in countries where survey outlines are uncertain. b) Coverage of detailed geological maps (1984) from Weber (1983).

cally updating) 1:5 000 000 scale gravity and aeromagnetic anomaly maps of its territory. The 1987 edition of the Magnetic Anomaly Map of Canada (Dods *et al.* 1987) was on display at the Exploration '87 meeting. A Bouguer anomaly map (scale 1:5 000 000) of the conterminous United States of America appeared in 1982, and 1987 has seen the publication of gravity and magnetic maps at the same scale for the whole of North America and the adjacent oceans (Geological Society of America 1987), using the latest digital colour-mapping technology described elsewhere in this volume.

In the case of the largest single piece of Precambrian crust, namely the continent of Africa, a compilation of all existing gravity survey data is currently being carried out by the University of Leeds in England. A further advantage of compilations of this kind is that they allow ready access to a vast body of published (but often not readily available) geophysical data which may far exceed, for example, the coverage of published geological maps. Perhaps 70 percent of Africa now has aeromagnetic coverage at scale 1:100 000 or better while geological maps at a comparable scale cover less than 5 percent of the continent (Figure 23.1). An aeromagnetic data base for the whole continent would clearly be a valuable asset to any exploration undertaking there.

HIDDEN TECTONIC FEATURES OF SUB-CONTINENTAL SCALE

One of the most outstanding conclusions to be drawn from studying continental scale areas of gravity and/or magnetic data is the division of Precambrian shields into provinces, each of which displays a characteristic "signature" or "thumbprint" in the geophysical anomaly pattern. The texture of the anomalies is particularly evident in aeromagnetic data, while the province boundaries, where one tectonic style comes into contact with another, are often accompanied by significant linear gravity anomalies. These tectonic divisions do not, of course, owe their recognition solely to geophysics, but were first recognised from geological observations of tectonic style, metamorphism and geochronology. However, geological observations require the visibility of outcrops. The geophysical methods serve to demonstrate continuity between areas of exposure and to provide a means of geological extrapolation into the unexposed areas. By way of example, Figure 23.2 illustrates the correlation between lineaments in the gravity anomaly pattern and the basement geology for western Australia, and demonstrates their continuity below areas of Phanerozoic cover.

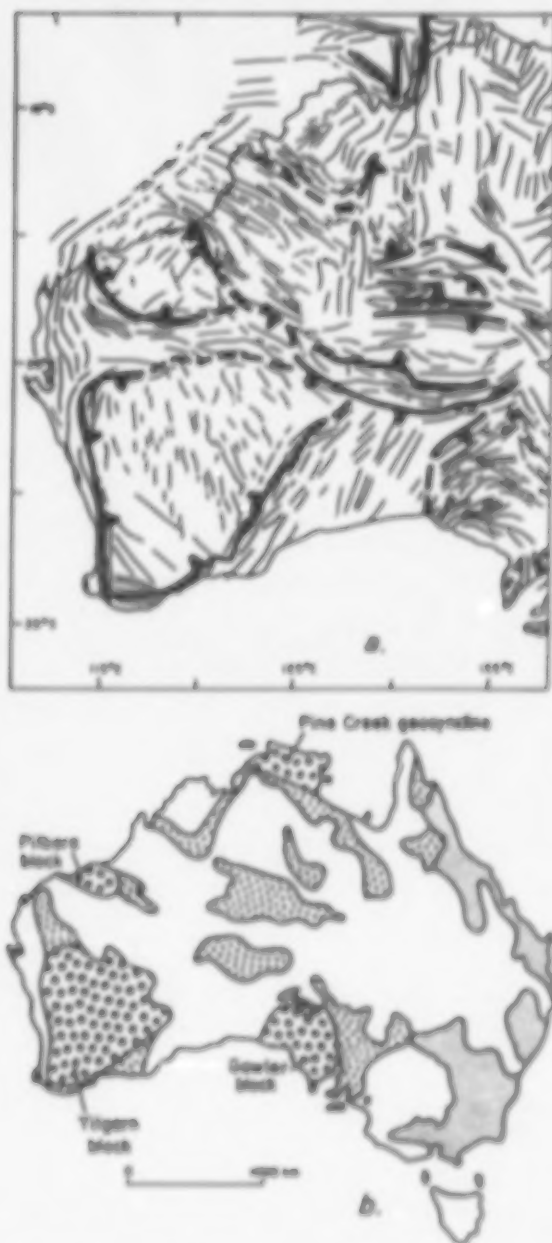


Figure 23.2. a) Crustal-block boundaries (heavy lines) in eastern Australia, inferred from gravity anomaly trends (thin lines). Anomalies following boundaries are of the Gibb and Thomas dipole type, the short's tooth indicating the older province (after Wellman 1975). b) Basement ages of Australia: Large stippling: Archean; medium stippling: Proterozoic; fine stippling: Phanerozoic; unstippled: cover rocks (from Wellman 1985). Note the continuity of gravity features in a) below the cover rocks shown in b).

In the case of the Canadian Shield, many of the province boundaries are interpreted as suture lines (sometimes cryptic) between Archean and/or Proterozoic proto-continents (Figure 23.3). Gibb and Thomas (1976) have noted that the typical gravity anomaly associated with such a suture has both a positive and a negative part, the positive part being situated on the side of the younger crustal block. This they interpret in terms of a slight increase in crustal density and crustal thickness with age and a corresponding isostatic adjustment at the base of the crust (Figure 23.4). This model has enjoyed some success as a generic type for modelling similar Precambrian sutures in other continents such as Australia (Wellman 1985), West Africa and South America (Lesquer and Loxis 1982) and South Africa (de Beer and Meyer 1984).

Two further examples of geological features of subcontinental scale which owe their discovery to geophysical mapping concern China and central southern Africa. Figure 23.5 shows the main features of the Bouguer anomaly field of the southern part of the People's Republic of China, taken from Zhuo *et al.* (1985). A distinct gradient of range about 70 mGal crosses the area in a NNE-SSW direction. A compilation of aeromagnetic data provided by workers at the Chengdu College of Geology (Plate 23.1, see Colour Folio near end of volume; Lin Qian, personal communication) shows that this gravity lineament also appears in the magnetic anomaly data, where a change in signature is evident between the magnetically "low" (blue) and smoothly varying areas in the west in the region of the Chengdu Basin and the "high" (red) areas in the east where many short wavelength variations in the magnetic field are evident. The southern Africa example deserves further elaboration, particularly since the frontier work in the Kalahari which gave rise to it commenced as an indirect result of a Botswana delegation's participation in the first of this series of conferences in Niagara Falls, 20 years ago.

GEOPHYSICAL MAPPING OF THE KALAHARI

The sands of the Kalahari, Cretaceous to Recent in age, occupy the largely inland-drainage area of the continental plateau (about 1000 m above sea level) in central southern Africa. Most of the area of Botswana falls within the Kalahari (Figure 23.6), denying the field geologist access to the Precambrian rocks which have been so economically productive in the neighbouring countries of South Africa, Namibia, Zimbabwe, and Zambia.

A reconnaissance gravity survey of the whole of Botswana (funded by the British government) was carried out in 1972 and 1973 and followed by a Canadian-funded aeromagnetic survey of the Kalahari area in 1973 and 1976 (Reeves 1985). More recently (1986), the Precambrian basement areas of

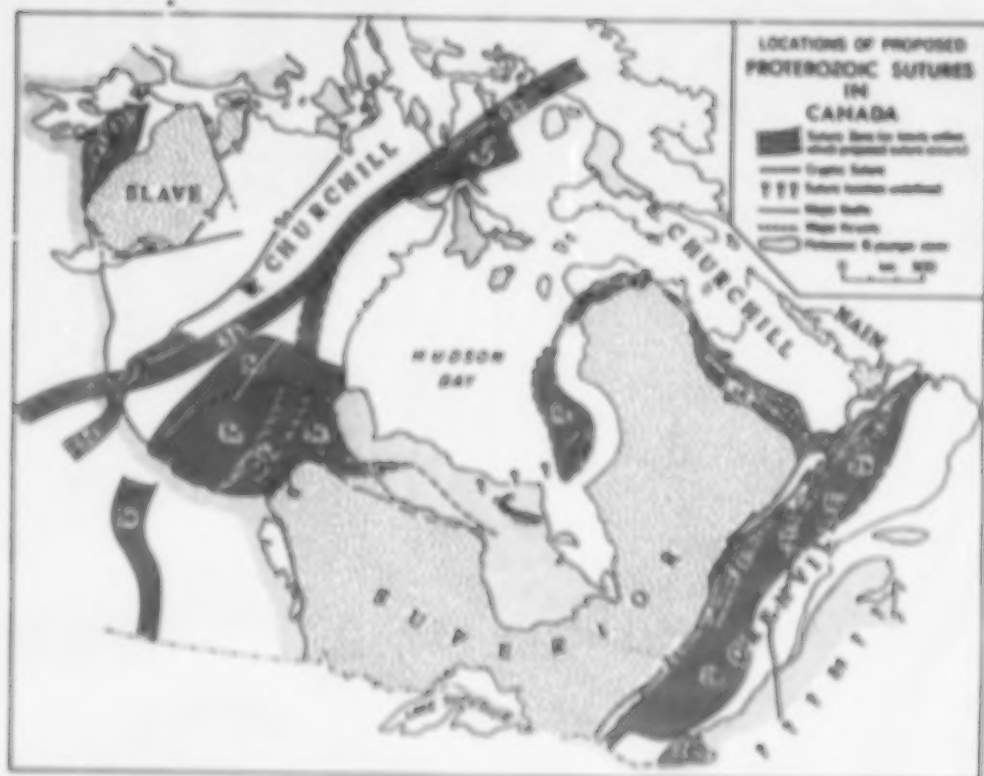


Figure 13.3. Location of proposed Proterozoic sutures in Canada (from Gibb et al. 1983).

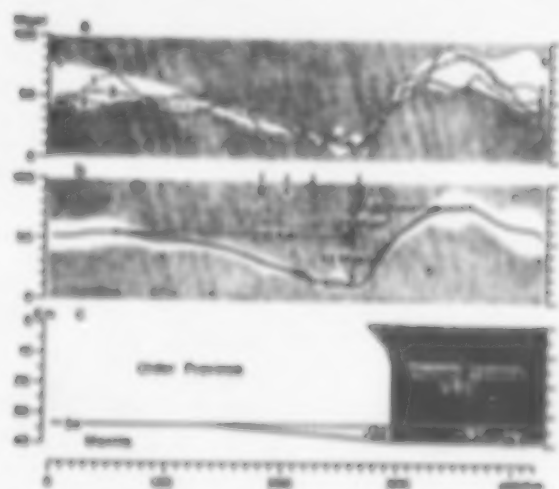


Figure 13.4. a) Bouguer anomaly profiles across five typical inter-province boundaries in the Canadian Shield. b) Gravity signature (type anomaly) derived by averaging profiles 1-5. Unshaded envelope is described by standard deviation calculated at 5 km intervals along profiles. Dashed line is the gravity effect of type model shown in (c). c) Type crustal structure derived from type anomaly. Density contrasts in g/cm^3 ; depths in km (From Gibb and Thomas 1976).

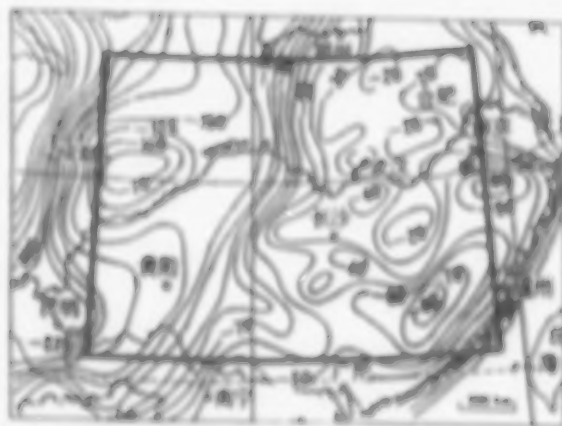


Figure 13.5. Gravity Bouguer anomaly map of central southern China (from Zhao et al. 1983). Meridians shown are 110 degrees and 120 degrees E, parallel is 30 degrees N. The heavy outline is the area between 104° and 118° E and 24° and 34° N which is shown in Plate 23.1.



Figure 23.6. Botswana in relation to the main geologic units of southern Africa: Kalahari cover (1), Karoo cover (2) and basement rocks (3-7). KV = Kaapvaal craton; L = Limpopo mobile belt; R = Rhodesian (Zimbabwean) craton; N = Namaqualand mobile belt; K = Kheis group; I = Irumide belt. The area covered by Figures 23.7a) and b) is indicated by heavy broken lines.

the eastern part of Botswana have been mapped aeromagnetically under a European Community development project, thus bringing Botswana into the swelling ranks of African countries having complete aeromagnetic survey coverage (see Figure 23.1a). The contribution of these undertakings to knowledge of the Precambrian basement in southern Africa has been considerable, particularly in southwest Botswana.

The national gravity survey of Botswana revealed a major and hitherto unsuspected north-south trend in western Botswana which was correlated with the north-south-striking folds seen in the rather isolated rocks outcropping some 300 km further south in the northern Cape Province of South Africa (Figure 23.7a)). Much greater detail was added by the aeromagnetic coverage, even at a flight-line spacing as wide as 4 km. The interpretation of the aeromagnetic data, extended south using the published aeromagnetic coverage of the northern Cape Province, is shown in Figure 23.7b). Four tectonic domains can be recognized:

1. In the east, the Archean basement which outcrops only very locally is interpreted to lie at only a small depth and to be covered increasingly to the west and north by Proterozoic supracrustal sequences, including a magnetically prominent ironstone horizon.
2. Towards longitude 23° E and as far north as latitude 23° N the platform cover becomes increasingly intensely folded, finally entering a north-south striking folded belt some 60 km in width which coincides with a distinct negative

gravity anomaly of amplitude about 30 mGal. On Figure 23.7b), this has the label "Kheis Belt".

3. North of latitude 27° S and immediately west of the Kheis Belt lies a band of intensely magnetic rocks some 10 km in width and 500 km in length which form a feature which has been given the name "Kalahari Line".
4. West of the Kalahari Line the geophysical evidence shows the magnetic basement to be buried at great depth (10 km or more) where it is presumably overlain by non-magnetic sediments. The upper parts of the sedimentary sequence contain dikes and sills of presumed mid-Jurassic age, and the host sediments include, at least in part, deposits of Karoo (late Carboniferous to early Jurassic) age.

The aeromagnetic interpretation was followed up by a limited program of test drilling funded by Canadian aid (Meixner and Peart 1984). This added valuable new stratigraphic information at locations remote from previous drilling. The geological synthesis of these results into a new concept of the geological framework of central southern Africa is shown in Plate 23.2 (see Colour Folio near end of volume). The contribution of the geophysical and drilling programs may be assessed by comparing Plate 23.2 and Figure 23.6.

Among the more important conclusions of this work to date are the following (Hutchins and Lynam 1985):

1. The Kalahari sand cover is generally rather thin, usually less than 100 m in thickness.
2. The granite-greenstone terrane of the Kaapvaal and Zimbabwean craton extends as far west as 22° E where it terminates against the Kalahari Line or the Kheis Fold Belt.
3. The Kheis Fold Belt has certain potential for economic mineralization within the area of thin Kalahari sand cover, akin to the base metal mineralization known further south at Copperton and Aggenys in the Cape Province of South Africa.
4. The highly magnetic rocks of the Kalahari Line were sampled (by drilling) and found to be layered cumulate gabbro or gabbroic norites (Meixner and Peart 1984) and dated at about 1000 Ma (Meixner, personal communication), in contrast to the 1800 Ma dates of the granitic rock in the Okwa outcrop area and the Archean ages of the craton to the east. The 1000 Ma age is in common with the rocks of the Namaqualand Belt in the extreme southwest of Figure 23.7 (a) and (b).
5. Thick coal seams occur within the Karoo sequence in the area, even though they are some 500 km remote from sites of existing coal production in eastern Botswana.

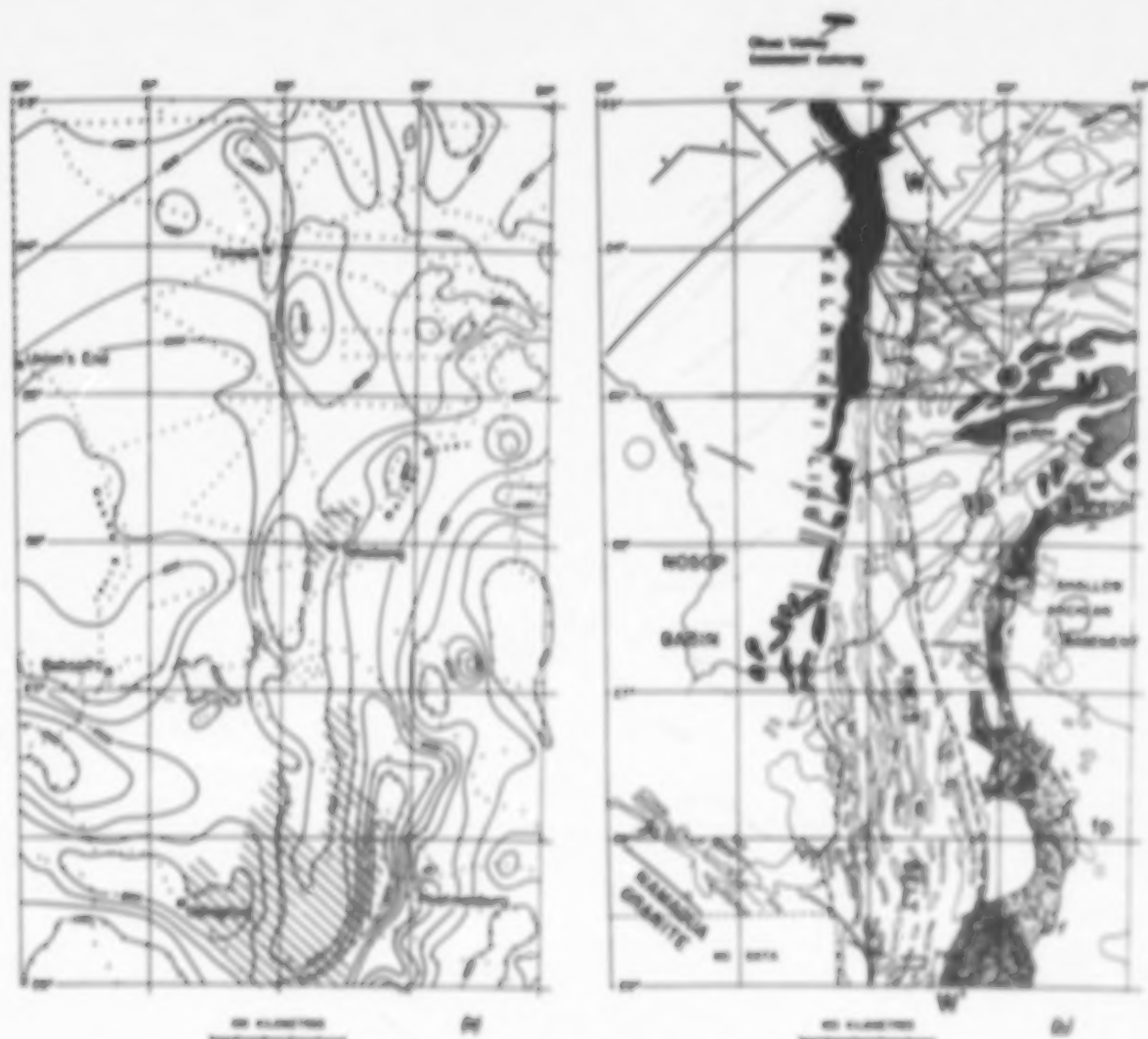


Figure 23.7. a) Bouguer γ -anomaly contours in the vicinity of the Kalahari line, which falls along the 22° E meridian. Contour interval, 10 mGal. Areas of sporadic outcrop of tightly folded Kheis and Mafic rocks (between Uptown, Postmasburg and Tlokweng) are shown by diagonal hatching. b) Outline interpretation of aeromagnetic data for the same area. Highly magnetic rocks of the Tlokweng complex, which marks the Kalahari line in Botswana, are shown solid black. W-W' = interpreted western limit of flat-lying Proterozoic cover rocks on the Archean basement; B = banded ironstones in the cover rocks; tp = thin Proterozoic cover; TP = thick Proterozoic cover; M = Molapo Formation ultramafic complex in southern Botswana. Outlines of other interpreted rock units are indicated by thin solid lines. Axes of broad magnetic anomalies originating below the Nossop basin are indicated by dotted lines. The international boundary between Botswana in the north and South Africa in the south is formed by the Nossop and Molapo rivers (from Reeves 1983).

6. The thick sediments west of the Kalahari Line have attracted attention as potential hydrocarbon exploration targets, with a seismic reflection profiling crew being mobilised in 1987 and more detailed gravity, magnetic and magnetotelluric studies scheduled for 1988.

This provides an excellent example of how a modest expenditure on geophysical mapping and

imaginative follow-up can produce a significant contribution to exploration in an exposureless terrain.

THE GEOPHYSICAL EXPRESSION OF GREENSTONE BELTS

MAPPING HIDDEN GREENSTONES

The pattern of limited areas of low-grade "greenstone" belts lying in a "sea" of granitoid rocks

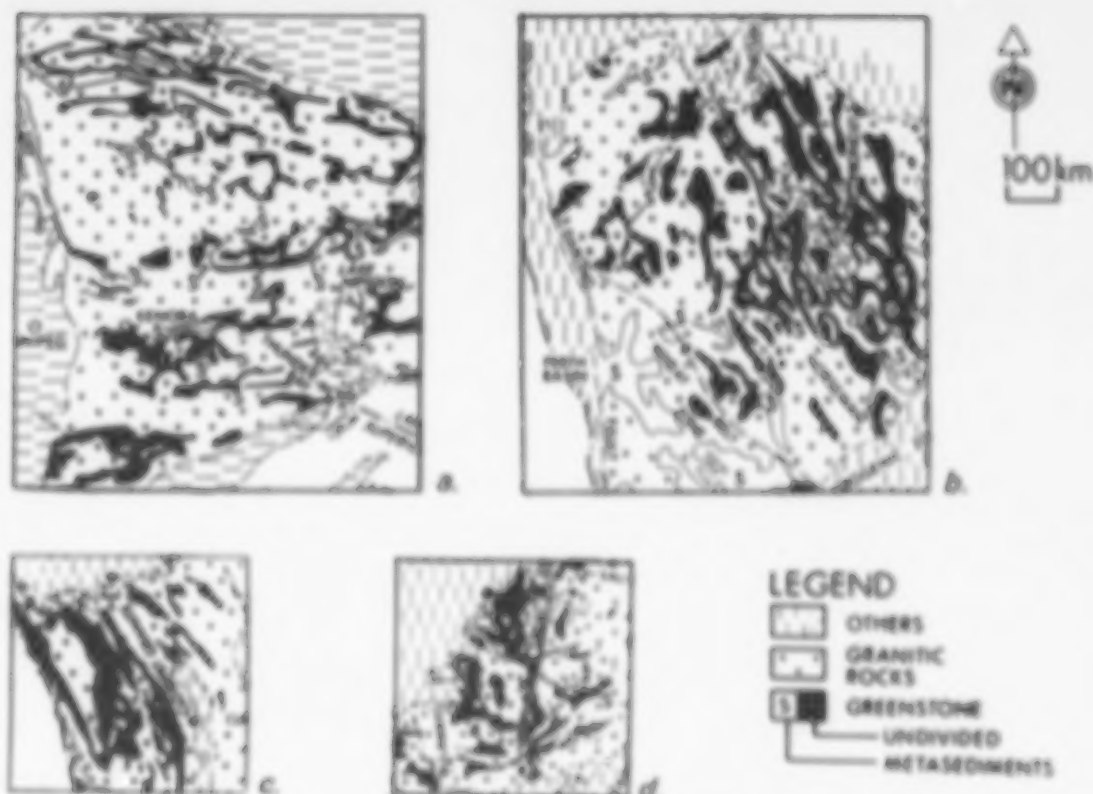


Figure 23.8. Typical patterns of greenstone belts in Precambrian metamorphic terrain on a common scale. a) southern Canadian Shield; b) Vilpurn block, Western Australia; c) Peninsular India; d) Zimbabwe (after Goodwin 1981).

is common to all the Archean areas of the world (Figure 23.8). By area, the greenstones usually occupy no more than about 20 percent of the presently exposed surface, whereas economically they contain some 80 percent of the mineralization, including principally gold and base metals. Being therefore 15 to 20 times more productive, they are obvious targets of "area selection" in any mineral exploration strategy. Any geophysical method which can define greenstone belts where they are hidden, for example, by thin surficial cover, is therefore potentially most valuable.

As a result of the high proportion of mafic volcanic rocks they often contain, the mean density of greenstone belts may be well above that of the surrounding granitoids. Greenstone belts therefore can give rise to clearly defined positive gravity anomalies. This is certainly the case in many parts of Africa. An example is shown in Figure 23.9 from the western part of the Zimbabwean craton in eastern Botswana. Here it is seen that even a reconnaissance gravity survey will detect the gravity anomaly over a small greenstone belt such as that at Tati (A in Figure 23.9). A larger belt (B) has a more extensive anomaly which is not confined to the outcrop area but may be followed below the cover of Kalahari sand

and Karoo sediments which occur to the west of the Archean outcrop area. The presence of the extension of the belt was demonstrated by shallow drilling designed to investigate the Karoo stratigraphy some 30 km from any known greenstone outcrop. Further west again, other positive gravity anomalies, designated C in Figure 23.9, suggest further targets for follow-up with more detailed surveys which could be expected to reveal new, as yet unseen, greenstone belts.

DEPTH-EXTENT OF GREENSTONE BELTS

Two approaches to quantitative modeling of source-geometry for the gravity anomalies due to greenstone belts have been tried over the years. One involves simple 2-D or 2.5-D modeling of elongate anomalies to give a cross-section of the causative body for a given positive density contrast based on rock samples collected at the surface. A typical result is shown in Figure 23.10 which relates to the Seronera greenstone belt in Tanzania. The other is "apparent density mapping" in which the gridded residual gravity anomaly field is inverted to give a density for the square vertical prism centered on each cell of the gridded data, the horizontal dimensions of each prism being equal to the gridded cell-size. Both ap-

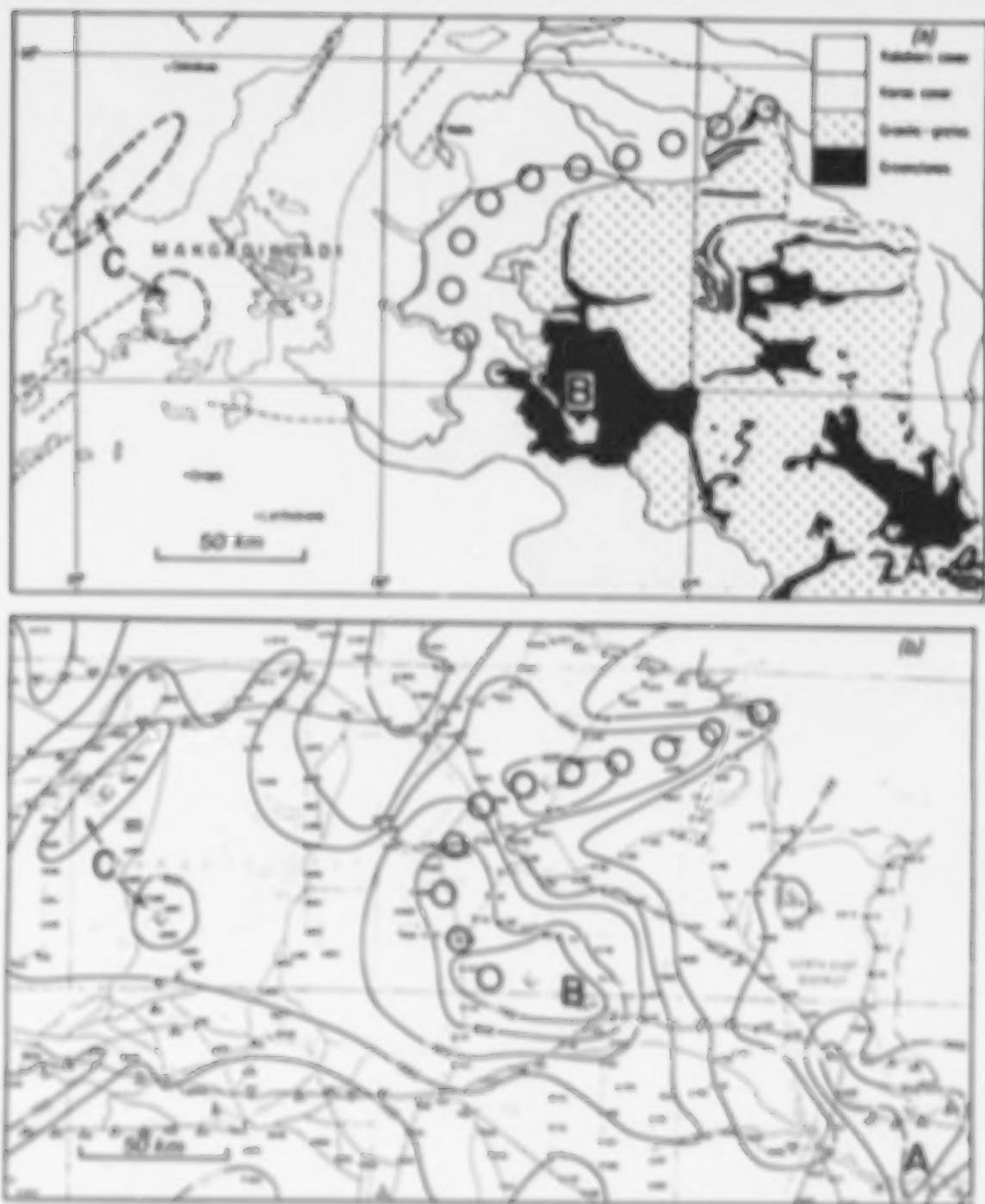


Figure 15.9. a) Simplified geological map of northeast Botswana. b) Bouguer gravity anomaly map of the same area, contour interval 10 mgal. A = Felsic greenstone belt; B = Monzonite greenstone belt as / is interpreted contours (solid) below younger cover rocks (Circle locations are common to both maps); C = interpreted, older greenstone belt (from Reeves 1985).

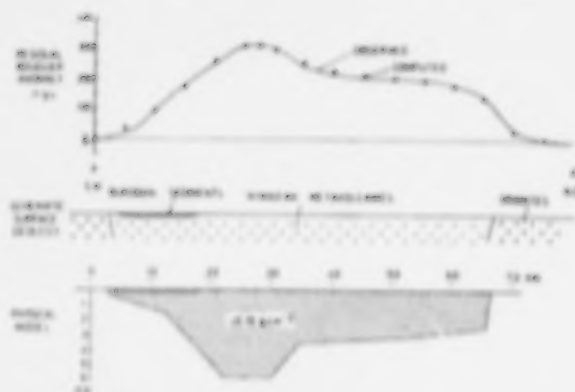


Figure 23.10. Top: Observed and computed residual gravity anomalies over the Seronera greenstone belt in Tanzania. Middle: Schematic surface geology. Bottom: Cross-section of theoretical 2D model giving rise to the "computed" anomaly above. (after Durracott 1976).

proaches use residual anomalies created by subtraction of a reasonable Bouguer anomaly background level or regional.

In the second approach, a common depth for the base of all the prisms has to be set in order to fully define the inversion. In areas where extensive surface sampling of rock densities has been carried out (e.g. Gupta and Grant 1985) it is found that, in order to bring the computed densities into agreement with those observed, the bases of the prisms should be situated at about 6 km depth.

This figure is in close agreement with that found from 2-D and 2.5-D modeling (such as Figure 23.10), as has been verified by a literature review and new interpretation of anomalies from many parts of the world (Ayele 1986).

To state this result concisely, and with due regard to non-uniqueness, it is concluded that, in order to account for observed gravity anomalies over Precambrian granite-greenstone terranes, the density inhomogeneities observed in surface rocks need not extend to a depth greater than about 6 km to account for all anomalies encountered.

The geological significance of this depth limitation to greenstone structures is as yet unclear, but it is independently confirmed by geoelectrical deep soundings over South African greenstones by de Beer and Stettler (in press). These authors also show that the low-grade granite-greenstone terranes have a high electrical resistivity (40 to 100×10^3 ohm metres) overlying a relatively low resistivity (5×10^3 ohm metres) layer starting at 6 to 10 km depth. In the Archean/Proterozoic high-grade terranes, such as the Limpopo Belt the high resistivity layer is absent, the 5×10^3 ohm metre layer extending to the surface.

THE MAGNETIC EXPRESSION OF GREENSTONE BELTS

Several authors (Hood *et al.* 1982; Grant 1985a) have demonstrated the strong correlation between regional magnetic lows and greenstone belts within the Superior Province of the Canadian Shield. This is an area of high magnetic inclination, where high magnetite concentrations would be expected to produce positive magnetic anomalies. It therefore follows, if predominantly induced magnetization is assumed, that Superior Province greenstones are, on average, depleted in magnetite with respect to their surrounding granitoid rocks. Further to the northwest, within the Western Churchill Province (see Figure 23.3), very similar greenstone-type magnetic anomalies are evident in areas which are seen to be fully granitized (Grant 1985a).

A similar situation was found during the interpretation of the aeromagnetic survey of Ivory Coast (Grant *et al.* 1980). In this case, many areas were found to have magnetic signatures typical of volcanic rocks or greenstones in places which were in fact mapped (from isolated outcrops) as granitic. Their geophysical character, however, suggested that their magnetic mineralogy has preserved a fabric similar to that which is commonly encountered in greenstone belts where iron-rich tholeiites alternate with Mg-rich tholeiites, felsic units, graywackes, and banded iron formations. In the region of Boundiali in northwest Ivory Coast they cover an area that is roughly $200 \text{ km} \times 500 \text{ km}$, which is typical of some of the larger greenstone belts in the Canadian Shield. They were interpreted as gneissic or granitoid rocks of volcano-sedimentary origin, a conclusion that was reached independently by a parallel photogeological interpretation (unpublished). If correct, this interpretation enlarges the potential search area for metallic ores in the Ivory Coast.

These observations serve as a reminder that the magnetic properties of rocks in bulk are almost entirely dependent on the magnetite they contain. To a considerable degree, therefore, a magnetic interpretation map is only a schematic representation of magnetite distribution. The reconciliation of such a map with a geological map is not straightforward; the field geologist is generally little concerned with the distribution of a mere accessory mineral like magnetite. These problems can be particularly severe in an area where metamorphism and deformation has reworked the bedrock repeatedly. The resulting distribution of magnetite may then reflect only a paleolithology or protolithology derived from the ancestral rock, or the distribution of areas favourable to magnetite generation or destruction during a particular metamorphic episode.

Boyd (1969) alluded to this when he remarked that an aeromagnetic survey in Uganda revealed two prominent geological trends, only one of which could be identified in the field. He suggested that "further work...remains to be done with the mag-

netic interpretation of metamorphic structures". Twenty years later, this remark still holds true.

One conclusion is that, whereas it is relatively straightforward to interpret aeromagnetic surveys in a structural way to show faults, folds, intrusions, contacts, etc., it is quite a different (and potentially misleading) exercise to try to name rock units solely on the basis of their magnetic signature or expression, i.e. to produce a lithologic interpretation. Grant (1985a, b) gives a comprehensive summary of the state of knowledge of the behaviour of magnetite in rocks and mineral environments over geological time and under various metamorphic and redox conditions. More recent studies begin to give momentum to the advancement of "magnetic petrology".

MAGNETIC PETROLOGY

Geophysical methods depend on variations in the physical properties (such as density and magnetization) of rocks *in situ* giving rise to changes in quantities (such as gravitational acceleration and scalar magnitude of the geomagnetic field) that can be measured remotely – at the earth's surface or in the air. Historically, a disproportionate effort has gone into collecting survey data, such as gravity and magnetic data, compared with rock property studies which could be used to help interpret variations in the geophysical anomaly fields. Recent studies of rock magnetism have included the study of magnetite evolution (creation and/or destruction) under realistic geological conditions and the measurement of a sufficiently large number of hand-specimens from an area to allow statistically significant results, despite high sample-to-sample variations.

The complexity of magnetite evolution is illustrated by Figure 23.11 which shows possible stages

of creation and destruction of magnetite during increasing levels of metamorphism for a rock which starts as a simple extrusive basalt (Wasilewski 1987). It is seen that several phases of magnetite destruction and creation are possible before consumption into an essentially non-magnetic mantle.

Other possibilities include the destruction of magnetite in fault zones, an excellent example of which, from the Precambrian shield of India, is given by Gupta *et al.* (Paper 76, this volume). In an exceedingly detailed ground magnetic survey for kimberlite exploration over some 1200 line-kilometres in an area of Precambrian rocks showing typically high and variable magnetic relief, broad linear zones were recognized where the magnetic profiles were featureless. Ground-truth investigations showed that these zones were occupied by sheared rocks with magnetic susceptibilities approaching zero over a width of several hundred metres, surrounded by typical basement rock assemblages which gave highly variable magnetic susceptibilities.

Magnetic anomalies over intrusive dikes are well-known. In fact, of all the dike-mapping techniques that are available, including air-photo and satellite imagery interpretation, magnetic survey may well be the most effective. The potential of dikes as fossil stress-indicators is gaining recognition (Halls 1982) and may indicate a new role for aeromagnetic surveys in shield areas. Meanwhile, Clark (1987) draws attention to the incidence of dikes in Australia where the rock material of the dike itself is totally non-magnetic (and presumably totally lacking in magnetite) but where the thermal metamorphism induced in the immediately adjacent rocks by dike emplacement has led to the creation of magnetite in the contact zones either side of the non-magnetic dike. In this way even a "non-magnetic" dike can give rise to a significant anomaly which may betray its presence on an aeromagnetic map.

In terms of rock property studies, a landmark undertaking has recently been completed through cooperation between the Swedish, Norwegian and Finnish Geological Surveys working in the northern Baltic Shield (Henkel 1987). Over 30 000 specimens were collected and measured for density, magnetic susceptibility, and natural remanent magnetization (NRM).

Figure 23.12 shows a frequency plot of magnetic susceptibility against density for the Precambrian rocks of the study area. It is seen here that whereas density varies continuously between 2.55 and 3.10 g cm⁻³ with a preponderance of lower (granitoid) densities, the distribution of magnetic susceptibilities is distinctly bimodal. The group with the lower susceptibility is essentially non-magnetic (or paramagnetic, 2×10^{-6} SI) whereas the other peaks at about 10^{-2} SI (0.02 SI). This bimodal distribution appears to be somewhat independent of major rock lithology and hence gives rise to a typically banded pattern of magnetic anomalies over the shield. This

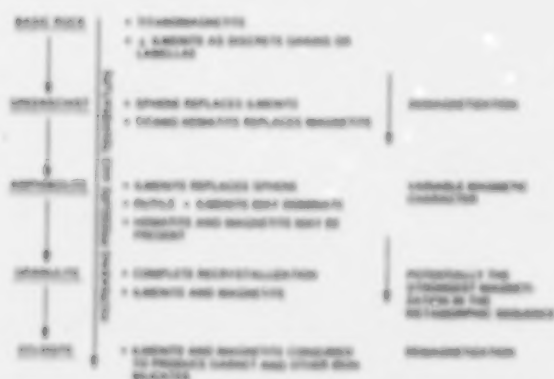


Figure 23.11. Scenario for Basalt rock metamorphism, indicating the possible repeated destruction and re-creation of magnetite in a simple basalt during increasing degrees of metamorphism (courtesy of P. Wasilewski).

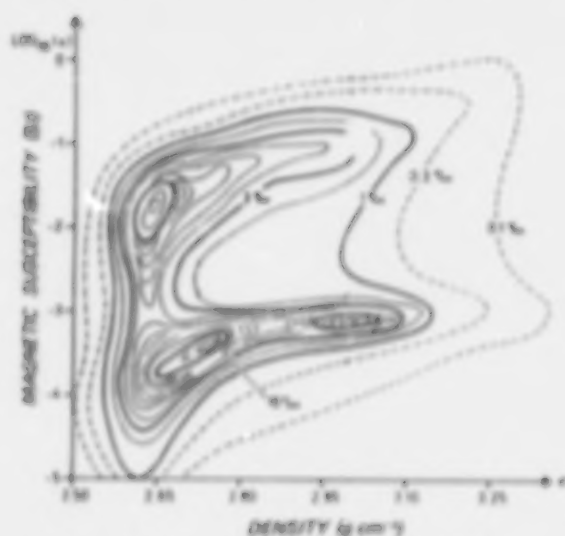


Figure 23.12. Frequency distribution of 30 000 Precambrian rock samples from northern Scandinavia tested for density and magnetic susceptibility (courtesy of H. Hekkel).



Figure 23.13. Frequency distribution of 30 000 Precambrian rock samples from northern Scandinavia: Koenigsberger ratio versus magnetic susceptibility (courtesy of H. Hekkel).

allows structural detail to be traced through most areas by aeromagnetic survey interpretation, but naturally tends to confound interpretation in terms of major lithological units.

It should be noted from Figure 23.12 that as basicity (and therefore density) increases there is a general tendency for magnetic susceptibility also to increase. However, some felsic rocks are just as magnetic as the average for mafic rocks, and some very mafic rocks in the lower susceptibility branch are totally non-magnetic.

Figure 23.13 shows the relationship between magnetic susceptibility and Koenigsberger ratio, Q . The simplifying assumption, common in aeromagnetic interpretation, that magnetization is entirely induced (and therefore in the direction of the present-day magnetic field) is clearly supported by these results in so far as the average Q for 30 000 Scandinavian rocks is only 0.2.

Three processes are shown by the study to affect particularly the occurrence of magnetite: a) amphibolite-granulite facies transition; b) serpentinization of ultramafic rocks and c) oxidation in fracture zones.

The full results of the Scandinavian study will, when published, make essential reading for the aeromagnetic interpreter.

CONCLUSIONS

Regional geophysical mapping — particularly gravity and magnetic anomaly mapping — over increasingly large areas is proving invaluable as a source of structural and tectonic information, particularly through its ability to allow geological features in the basement to be traced through areas of superficial cover where the Precambrian rocks are obscured from direct observation.

The value of gravity and magnetic data sets at a continental scale increases as they become more complete, more detailed, and more readily available to potential users. They now enjoy an established role as fundamental geo-data sets which should be used imaginatively in the exploration cycle in conjunction with geological maps, satellite images, mineral occurrence maps, etc. when working at scales in the range 1:1 000 000 to 1:50 000, i.e. in the selection of those areas of interest for a more intensive exploration campaign.

Examples from predominantly Precambrian areas of southern Africa given here show success in the discovery of hidden sedimentary basins with potential for hydrocarbon exploration and of hidden greenstone belts with potential for base- and precious-metal mineralization.

Better knowledge of the rock properties which give rise to gravity and magnetic anomalies — particularly the behaviour of magnetite over geological time — may be expected to materially assist in the

qualitative and quantitative interpretation of gravity and magnetic anomalies, particularly in extensive metamorphic areas where geophysical data may reveal (for example) a paleolithology which is not readily mapped by any other means.

In an age of truly integrated exploration methods, an enlightened perception of the geology is a prerequisite in any systematic search for economic mineralization. In the years ahead the geological interpretation of regional geophysical data can be expected to contribute materially to a better understanding of geology in general and Precambrian geology in particular.

ACKNOWLEDGMENTS

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I wish to acknowledge the inspiration of the late Fraser Grant whose personal contribution to many of the ideas discussed here was sadly cut short by his untimely death in 1984.

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24. Progress in Interpreting and Following Up Aeromagnetic Surveys

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At the Exploration '77 meeting in Ottawa, Allan Spector and Wilf Parker presented a paper entitled *Computer Compilation and Interpretation of Geophysical Data* (Spector and Parker 1979). At that time, in 1977, we were on the threshold of an exciting period in the development of new "tools" for use in both airborne and ground magnetics, including higher resolution instrumentation for airborne surveys, the development of microprocessor-controlled field magnetometers and gradiometers of much greater accuracy, reliability, and data storage capability; and the development of reliable, cost-effective techniques for data enhancement and modeling. Since that time, many of these developments have been realized, in particular the improvements in overall survey quality, caused by a factor of ten improvement in magnetometer accuracy and navigational positioning, and the complete conversion to digital acquisition by all the survey companies. Microprocessor-based ground magnetometers are now being processed by all the major geophysical instrument manufacturers. The production of data diskettes and the storing of surveys in memory magnetometers is as routine today as the fledgling electronic notebooks and cartridge tapes were in 1977.

Data enhancement techniques are of particular importance in the mineral and hydrocarbon exploration fields. Data enhancement means the process of highlighting or subduing a particular desired pattern or signature within the overall magnetic field that has been sampled. Since the early 1970s, examples of these data enhancement images have become relatively common. The example illustrated in Plate 24.1 (see Colour Folio near back of book) is taken from high resolution magnetic coverage over the State of Minnesota, illustrating the total field, as an Applikon ink jet colour plot, enhanced by the addition of an artificial sun illumination. In the years following 1977, these processed images became available over selected areas using what digital data sets were available, and produced by relatively few companies.

The production and availability of these images in the last ten years and the ease and reliability of data enhancement has contributed greatly to our progress in aeromagnetic interpretation.

On a super regional scale, we have completed or are in the process of compiling extremely large data sets over the North American Continent. Compilations of this magnitude will facilitate processing and interpretations at a scale only dreamed of in the 1970s.

Projects for similar compilations at scales of 1:5 000 000 and 1:1 000 000 over the African and South American continents and continental margins are at the initial stages. The completion of these projects will facilitate large-scale basin analyses and the interpretation of complete geological provinces that up until now have not been contemplated. With the advent of these large data bases, the time period and cost for acquiring the basic geological framework for a prospective area has been greatly reduced.

The display of magnetic data using image analysis and data enhancement techniques has shown significant advances with the advent of readily accessible computer hardware and workstations. Plate 24.2 illustrates an example of image analysis techniques applied to aeromagnetic data within the PC environment. Advances in image processing systems and the accessibility of PC's as workstations and terminals have brought about significant improvements in the quality of aeromagnetic interpretation.

Within the last few years, computer hardware and software technology has moved away from the "white coats in the air-conditioned back room" to the state where geophysicists and geologists may generate processed or enhanced products as the routine initial stage of an aeromagnetic interpretation.

The available algorithms that may be used for aeromagnetic interpretation have also improved with the advent of new techniques for variable depth susceptibility mapping (Misener et al. 1984), methods for continuing fields onto uneven surfaces and for integration or "layering" of digital magnetic images with complementary datasets such as topography, gravity, geochemistry, and most recently with satellite and airborne radar images (Kowalik and Glenn 1987).

These processes are but the first step in the important task of geological interpretation, by which we mean:

- the determination of the distribution and geometry of magnetic sources
- the recognition of structural features and lithologic boundaries through changes in magnetic trends and textures

The determination of the distribution of magnetic sources and their pertinent parameters has been revolutionized on two fronts:

- the availability of fully interactive modeling programs (Reeves 1981) on the PC as illustrated in Figure 24.1
- the capability for the systematic modeling of large data sets

As an example, thousands of line kilometres of airborne data may be processed automatically on an anomaly by anomaly basis, leading to a magnetic body plot that facilitates the structural interpretation of an area. Plates 24.3 and 24.4 show an example of this technique being used in Central Africa (Pateron 1985). Plate 24.5 shows the total magnetic field over an area that exhibits Precambrian basement rocks in the north and late Precambrian and younger shelf sediments overlying basement to the south. Plate 24.4 shows a combination of the auto-

matic modeling results, the colour image of the basement topography derived from these model depths, and an initial structural interpretation.

In a more detailed sense, modeling may be combined with other data enhancement techniques to lead to an enhanced lithologic interpretation. Plate 24.5 shows the total magnetic field over a portion of a semi-detailed (400 m line spacing) survey in the Superior Province of Canada. Plate 24.6 illustrates the automatic modeling results superimposed on a calculated susceptibility map. The improved magnetic image (i.e. the susceptibility map), when combined with the hard data resulting from the modeling results, leads to a more reliable lithologic interpretation.

The recognition of structural features and lithologic boundaries now results in the routine creation of pseudogeology maps, based on the classification and identification of magnetic signature parameters such as lineation, texture, amplitude, and shape. The major contribution of the improved image analysis and data enhancement techniques in the last decade has been to supply the interpreter with a much clearer picture of these parameters and hence allow a more definitive interpretation.

In many cases of aeromagnetic interpretation, even when the geological framework on an area is known, aeromagnetism can help to identify a particular structural/lithological target. Plate 24.7 shows the high resolution total magnetic field data over a deep carbonate basin; the target signatures were zones associated with basement faults and late stage volcanics that may act as controls for Sedex (Sedimentary-Exhalative) type mineralization. The initial processed image, shown in Plate 24.8, is a regional-residual separation in order to remove the large regional component caused by extrusive rocks near the basement surface. In order to obtain a better resolution of the obvious residual features, this image was pole reduced and downward continued to a depth 3 km below the ground, close to the basement surface. The first vertical derivative of this field was calculated and is shown in Plate 24.9. Major east-west structures may be clearly identified on Plate 24.9, along with indications of faulting subparallel to stratigraphy and numerous cross-trending features. The enhanced north-south lineations had been interpreted previously as basement faults; however, they are in fact, due to minor errors in the original line-to-line data leveling that was not evident on the total field map.

In order to eliminate these spurious artifacts, a directional filter was applied resulting in the final image shown in Plate 24.10. On this image (Plate 24.11), faults, lithologic boundaries and some important intrusive events have been identified.

The evolution towards our final image was governed by an attempt to enhance the geophysical signatures of known or suspected geological patterns. Herein lies the major benefit of the recent advances

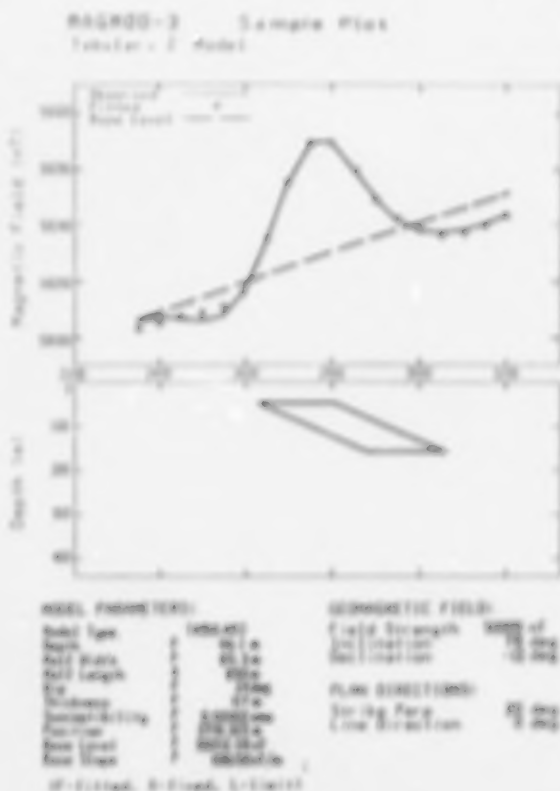


Figure 24.1. Interactive magnetic modeling. 3-D isobaric body.

in image analysis and processing: our ability to generate images that can be used to interpret lineations, textures, and shapes that are much closer in appearance to their true geological sources.

The aforementioned interpretation and processing example embodies a further important aspect or progression that has taken place in the last decade. The geophysicist must now not only be concerned with interpreting or proposing a distribution of magnetite that best fits the observed data or enhanced image, but also a distribution that is consistent with the mapped geology and with reasonable geological models. Mathematically this means that we have been able to reduce the non-uniqueness problem by greatly reducing the number of possible answers. Realistically what is happening is that a good interpretation geophysicist today must become more and more part economic and part structural geologist and, in fact, many geologists today are carrying out the geophysical interpretation of aeromagnetic images.

The closer integration that we have achieved between the enhanced images of the magnetic field and the underlying geological sources has initiated developments in the examination of the relationships between magnetite distribution and regional/detailed and economic geology (Grant 1985a, 1985b). These somewhat less spectacular developments have occurred on two fronts. In the fields of theoretical and experimental petrochemistry and mineralogy, progress has been made in understanding the stability and distribution of the magnetite family of minerals in various geochemical and metamorphic environments. This has helped us to relate magnetic textures to geologic processes, including both genesis and metamorphic overprinting. On another front, the sampling and analysis of rock magnetic susceptibilities and remanence characteristics has changed from the traditional study of rocks for geological interpretation. Within the next decade, as we obtain access to larger and more diverse datasets on the distribution of magnetite within various geological settings, we will be able to further reduce the ambiguity of our interpretations.

The introduction of microprocessor-based magnetometers has advanced the art of ground follow-up of aeromagnetic targets. In the majority of cases today, these targets are no longer simply anomalous "bull's eyes" or linear iron formations. We have progressed to a level of sophistication where we are able to design follow-up programs to delineate mafic-felsic contacts within a volcanic sequence, as well as derived sediments; we can recognize and delineate alteration zones and regions of major faulting and minor crosscutting shear zones; and, in many cases, we can outline intrusive features and indicate their geometric relationships, age, and zonation. In medium to high grade metamorphic environments, we are able, with the use of sensitive gradiometer measurements, to separate the various schists and

gneisses and to indicate their probable ancestry back through the metamorphic event.

Within the last two years, the advances in image analysis have joined this new generation of ground magnetometers in order to produce final enhanced products in the field. Plate 24.12 illustrates the culmination of field image analysis: the production i.e., both total field and enhanced products in colour and contour form. This type of magnetic map, generated using a mainframe computer and a large colour plotter in 1977, is being produced by a field-portable PC computer and an off-the-shelf printer plotter in 1987.

At the conclusion of the paper on aeromagnetism at Exploration '77, Spector and Parker (Spector and Parker 1979) forecast that "computer languages will continue to become more powerful and easier to use and computer operating systems and user programs will allow greater usage of interactive terminals by geophysicists." We believe that this forecast has been exceeded.

Advances in the next decade will be focused on five areas of research:

1. We will have completed a number, possibly three, continent-wide compilations of aeromagnetic data.
2. A more standardized and representative physical data base will become available.
3. Use of Global Positioning Systems (G.P.S.) by airborne survey contractors will result in substantial increases in coverage and reliability of aeromagnetic data.
4. Universal geophysical data bases will be more readily available and will incorporate topography, gravity and radar and other satellite images with the aeromagnetic data.
5. By the end of the next decade, geoscientists will be generating complex structural and possibly lithological maps based on aeromagnetic interpretations with the aid of pattern recognition algorithms and artificial intelligence.

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Geochemical Methods: Their Application to Ore Exploration



25. Bedrock Geochemistry in Mineral Exploration

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ABSTRACT

Bedrock geochemistry is defined as the measurement and interpretation of chemical parameters of bedrock as a function of their spatial or genetic relation to mineralization — including the measurement of elements from partial extractions, the composition of mineral separates, and the total or absolute chemical composition. The applications, at all levels of exploration, are divided into three broad categories: mineralization genetically associated with intrusive rocks; syngenetic mineralization associated with volcanic and sedimentary rocks; and vein-type mineralization in any rock type.

The essential conclusions presented at Exploration '77 have been substantiated, and bedrock geochemistry is now routinely used in exploration. Increasing attention has been given to the use of fluid inclusions (especially for gold exploration) and of rare earth elements for deposits of plutonic and volcanic association.

Whereas many elements give a response in particular cases, a suite of less than twelve elements is adequate for general application to particular classes of deposits. In addition to the ore elements, these are: K, Mg, Na, Ca, Rb, Sr, Ba, and Li for identification of specialized plutonic and local-scale exploration for porphyry deposits; Fe, Mn, Na, K, Ca, and Mg for massive sulphides at all exploration scales; and As, Sb, Te, and Bi for vein and replacement deposits. The latter elements are especially useful for gold exploration, although new analytical techniques for ppb Au make it one of the best indicators.

INTRODUCTION

Measurement of variations in the chemical composition of bedrock as a guide to mineralization has been used for at least a century (Curtis 1884; Finlayson 1910). Bedrock geochemistry ("litho-geochemistry" or, as it is called in this paper, "rock geochemistry") as a distinct and practical technique used in mineral exploration in English-speaking countries dates only from work done in the late 1960s (e.g. Cameron *et al.* 1971; Garrett 1971; Garrett and Farnas 1971). Its establishment as a routine exploration method was due to a variety of factors including the development of atomic absorption spectrometry (AAS) and subsequently, inductively coupled plasma optical emission spectroscopy (ICP-OES); the increasing availability of computers

to process large data sets; application of multivariate statistics to assist in data interpretation; a vastly improved understanding of the genesis of ore deposits; and mounting pressure to design techniques to find blind deposits.

In this paper, rock geochemistry includes the measurement and interpretation of any chemical parameter of bedrock as a function of its spatial or genetic relation to mineralization. Geochemical patterns in bedrock that can be related to mineralization are referred to as "primary" dispersion patterns regardless of whether they are epigenetic or syngenetic, or whether they have arisen from primary or secondary processes (this is essentially the usage advocated by James 1967).

The first major review of exploration rock geochemistry was given at Exploration '77 (Garrett and Nichol 1979); subsequently a book was devoted to the subject in the Exploration Geochemistry Handbook Series (Garrett 1982). Thus, the broad principles and salient conclusions will be treated only briefly here, and the main focus will be on work done over the last decade.

The present chemical composition of a rock sample is a reflection of the entire geological history of the rock — its original composition and the results of diagenesis, metamorphism, metasomatism, and weathering, as well as alteration associated with a mineralizing event. Insofar as the interpretation of rock geochemical data depends upon the interpretation of the geological environment, the geochemical response to mineralization is considered in relation to three main types of deposits:

- deposits of plutonic association
- stratiform deposits of volcanic and sedimentary association
- vein- and replacement-type deposits

This classification cannot be regarded as rigorous as many vein-type deposits have a clear plutonic association, but it is convenient in terms of geochemical responses.

Within each group the geochemical response is considered, as far as possible, in terms of exploration scale as follows:

- regional: large-scale responses that can discriminate between productive and barren terranes
- local- and mine-scale: responses that can be detected up to 1 to 2 km from individual deposits, and responses limited to the immediate wall rock of deposits.

DEPOSITS OF PLUTONIC ASSOCIATION

REGIONAL-SCALE EXPLORATION

Characteristic mineralization associated with granitoids can be grouped into two broad categories (Strong 1981):

- granophyre deposits of Sn, W, U, Mo, and the "rare" metals in quartz-rich leucocratic granitoids
- porphyry deposits of Cu(Au) and Mo in granitoid rocks of mainly intermediate composition

Recent genetic classifications (as in Chappell and White 1974) centre around the S-type granitoids associated with Sn-U mineralization (derived from a sedimentary protolith), and the I-type granitoids associated with Cu-Mo, porphyry-type mineralization (derived from an igneous protolith). Other major classification schemes include those of Ishihara (1977, 1981), Tasson *et al.* (1982), and Tasson (1984).

Plant *et al.* (1980, 1982) question the validity of a rigid application of the Chappell and White classifications and assert, as do many other authors (e.g. Jackson and Ramsey 1983; Strong 1981; Taylor and Fryer 1982), that water is the most important ingredient for rare metal accumulations. They argue that the protolith for S-type granites needs to be wet sediments.

The Porphyries

There is no obvious geochemical distinction between granitoids which host Cu-Mo porphyry deposits and otherwise similar granitoids that are barren. Limited data indicate that the mineralized granitoids occur in batholiths that are enriched in Cu (Brubaker and White 1971; Putnam 1971; McCarthy and Gunt 1978). Gwinn (1982) noted that in any particular region there is a trend of increasing K, Rb, and Rb/Sr ratios, and decreasing K/Rb ratios from non-mineralized to mineralized rocks. The absolute levels of concentration and the ratios are, however, different in each region. A generally applicable background or threshold cannot be assumed (Figure 25.1 and Figure 25.2).

In an investigation of two large Mo-W deposits associated with small (less than 0.2 km²) acid-intermediate rocks in sedimentary and volcanic rocks of Proterozoic age in the Nanhai area of Henan in China, Zhang *et al.* (1984) collected 6293 samples from a 100 x 100 m grid over 44.5 km² and from drillholes in two deposits. A large zoned halo of 32 km² occurs over the ore field — an inner zone of Mo, W, Sn, and F (where the known Mo-W deposits occur within the greatest Mo anomaly); a middle zone of Cu and Zn (where there are some small base metal deposits); and an outer zone of Pb, Ag, and Au.



Figure 25.1. Variation of Rb and Rb/Sr in barren and mineralized granitoids. Data from a variety of sources given in Gwinn (1982). Gwinn and Schandier (in press) see also Figure 25.2.

Nurmi (1984, 1985) studied 49 Proterozoic granitoids in 21 areas of Finland, including ten with Mo and/or Cu mineralization and some with Au. Based on 1 000 samples — analyzed for SiO₂, TiO₂, Al₂O₃, FeO, MgO, CaO, Na₂O, K₂O, P₂O₅, Rb, Sr, Ba, Cs, Sc, Co, Pb, Zn, La, Sm, U, and Th — only Cu showed anomalies of regional extent. Likely Cu mineralized phases could be detected by systematic sampling at a density of 1 to 3 samples/km². Moreover, Cu has an abnormally high variance in productive phases (see also Gwinn 1982). Copper-poor Mo mineralization may not be detected in this way. All Finnish mineralized Proterozoic granitoids have lower K/Rb ratios than porphyry deposits of North America and Chile (Figure 25.2). Nurmi (1984, 1985) concluded that petrochemical relations are not helpful on a regional scale except to assist in the identification of I-type granites. Large-scale anomalies of K and Rb/Sr due to post-magmatic metamorphic K-alteration are not necessarily related to mineralization.

Sn, U, and W Mineralization

Granitoids that are host to Sn, U, W, and rare metals are commonly referred to as "specialized". They



Figure 25.1. Variation of Rb/Sr and Sr/Ba in barren and mineralized granitoids. Granitoids referred to in text are: 1. Sardinia, mineralized; 2. Sardinia, barren; 3. Arabian Shield; 4. Carrigrohilly (U.K.); 5. Seagull (Canada); 6. Marshe (Australia); 7. Enns (Austria); 8. Vilpuri (Finland); 9. Suomu (Finland); 10. Southdown (Finland); 11. New Zealand W-bearing granitoids. Note that the main production from the Marshe and Enns (Austria) 'ore' granites has been W and Sn, respectively. Source of data for 1-3 and 5-10 given in this paper; all other sources given in Gowan (1982); & Gowan and Ashenden (in press).

tend to be siliceous and peraluminous and are characteristically enriched in such elements as Sn, U, Th, Rb, F, Li, W, Ta, Ba, S, Mo, Nb, Zr, Y, and Zr and are generally low in CaO, MgO, Ba, Sr, Co, and V. Specialized granitoids genetically related to Sn and U mineralization are clearly defined by Rb-Sr and, especially, Rb-Sr-K-Rb plots (Figures 25.1 and 25.2).

Characterization of a granitoid as specialized and highly evolved does not, however, necessarily imply economic mineralization. The Carrigrohilly granite in the U.K. and the plutonic granite of the Arabian Shield fall within the Sn-U field (Figure 25.2); both have Sn mineralization, but in neither case is it economic.

Notwithstanding the above caveat, all Sn and U granitoids for which analytical data are available fall

within the specialized granitoid zones shown in Figure 25.2. Those of eastern Australia, the U.S., northern Canada, and Nigeria were discussed by Gowan (1982) and Gowan and Ashenden (in press). Data for the Seagull batholith in the Yukon Territory of Canada (Mason *et al.* 1982), which has no vein mineralization within and close to the batholith, and for the Sn-W-Mo granites of Sardinia (Buse 1981), which lie within the specialized granitoid zone (Figure 25.2), confirm this conclusion.

The content of Sn itself has been widely used as a predictor for Sn-mineralized granitoids (Gowan 1982). Whereas it is true that higher Sn contents denote a higher probability of Sn mineralization, not all high Sn granites are host to economic Sn deposits, and some low-Sn granites do have associated Sn deposits.

From limited data on granitoids dominantly specialized with W, it appears that they lie close to the boundary between the Sn-U specialized granitoids and other granitoids. This is shown by the Marshe Granite (southeast Australia) that is host to the Mount Carbine wolfram mine and the New Zealand tungsten-bearing granites (Figure 25.2).

Kersh (1986) suggested that the largest W-skarns are associated with evolved I-type granitoids with Rb/Sr ratios of about 1.0 (e.g. Maching and Carrington in the Yukon-N.W.T. area). Other smaller skarns are associated with less evolved I-type granitoids; the Rb/Sr ratio is about 0.4. These conclusions are consistent with the data in Figure 25.2.

Vinard *et al.* (1981) indicated that the W-Sn granite of Regade (Portugal) is enriched in Sn, W, Li, Cs, F, Ta, Rb, F, and U and is depleted in Sr, Th, and Zr. Gail *et al.* (1981) sampled the 147 km² batholith at the Vilpuri Cu-W deposit that occurs in intermediate basic volcanic rocks close to the eastern margin of the Hameenkyrvi Batholith in southern Finland (it lies within the Rb-Sr-K-Rb zone of other Finnish granitoids, Figure 25.2). Sampling was at a density of one sample/km², with additional samples taken near to mineralization. The highest K₂O and Na₂O contents occur in the eastern portion of the batholith closest to mineralization. Enhanced levels of As, Cu, W, and Sn also occur along the eastern margin. Gail and his co-workers suggested that Cu-W targets are defined by anomalous As, Cu, W, and Sn, and high K₂O.

Use of Mineral Separates and Halogens

Attempts to characterize mineralized granitoids by total and H₂O-soluble halogens in whole rock and feldspar, and by base metals and other elements in veins and halogens, were reviewed by Gowan and Nichol (1979) and Gowan (1982). Gowan (1982) concluded that these studies yield, at best, equivocal results. Halogens in whole rock have characteristic values for each major intrusion but have no consistent relation to the presence or absence of mineralization. The content of halogens in feldspar varies de-

pending upon whether the biotite is magmatic, hydrothermal, or replacement in origin. Base metals in mineral separates are slightly more promising but no generally applicable relation to mineralization is apparent.

Use of Rare Earths

In igneous processes light rare earth elements (LREE, La-Sm) behave as incompatible elements because of their large ionic radii. They tend to be enriched in the last phases of crystallization with K, Rb, Cs, U, Th, and Zr. Heavy rare earth elements (HREE, Gd-Lu) have smaller radii and will substitute for other elements, particularly Ca, in rock-forming minerals.

The degree and manner in which REE patterns reflect hydrothermal alteration and mineralizing processes is a matter of some debate. In a useful review of the likely responses for plutonic-associated mineralization, Taylor and Fryer (1983) concluded that in porphyry environments (Figure 25.3), early K-alteration is produced by highly saline hydrothermal fluids expelled from a calc-alkalic magma. LREE and intermediate REE are enriched, and HREE are depleted; Eu is relatively enriched because of its divalent behaviour under conditions of low fO_2 . Subsequent incursions of meteoric hydrothermal fluids with a decrease in temperature and pH, and an increase in fluid:rock ratios leads to moderate (propylitic) REE leaching. Intermediate HREE are progressively less soluble in aqueous chloride solutions. Introduction of other anions, espe-

cially F^- and CO_3^{2-} , allows the removal of HREE in phyllic alteration. Under the latter conditions in a porphyry environment, Cu and Mo would also be mobile. Deposition of these metals should be accompanied by the previously leached REE giving a pattern of relatively enriched LREE and HREE.

Taylor and Fryer (1983) pointed out that the stability of REE fluoride and REE carbonate complexes increases from La to Yb; thus, in situations where these anions are present there should be fractionation of HREE. This appears to be the case for the Davis Lake tin deposit at East Kemptville (Nova Scotia, Canada). It occurs within the South Mountain Batholith which is chiefly biotite granodiorite intruded by smaller bodies of monzogranite and leucocratic monzogranite. The Sn-W-Cu-Mo mineralization is confined to the latter rock type (Chatterjee *et al.* 1983). There is a general decline in REE from the granodiorite to the monzogranite. The leucocratic monzogranite shows further loss of LREE, but there is an increase in HREE. Muecke and Clarke (1981) concluded that, whereas fractional crystallization could account for the difference between monzogranite and granodiorite, the pattern in leucocratic monzogranite indicates interaction with fluoride-rich solutions. According to Chatterjee and Strong (1984, 1985), increasing alteration at Davis Lake is reflected by a decrease in LREE and the Eu anomaly, and a slight increase in HREE. This

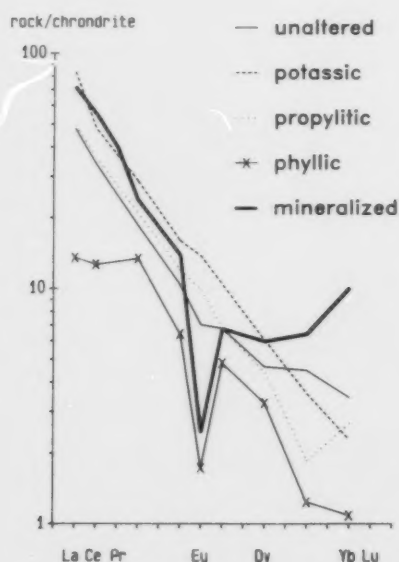


Figure 25.3. REE distribution in unaltered, potassic altered, propylitic, and phyllic granodiorite porphyry (Bakircay, Turkey), and mineralized porphyry (Climax, Colorado, USA) (compiled from Taylor and Fryer 1983).

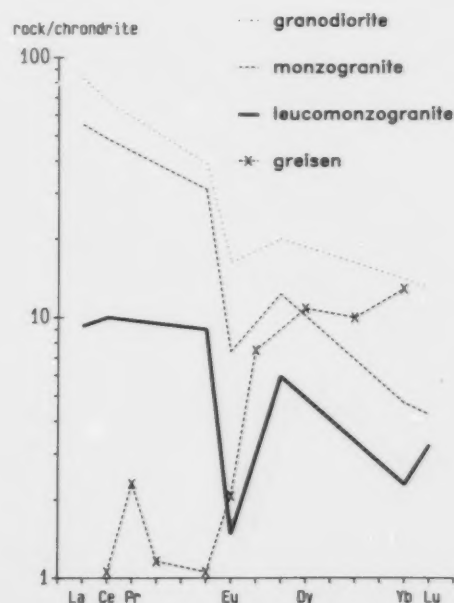


Figure 25.4. REE distribution in rocks from the South Mountain Batholith, Nova Scotia, Canada (data from Muecke and Clarke 1981). The greisen is from the area of the East Kemptville tin deposit at Davis Lake (hosted by leucomonzogranite). Davis Lake greisen data from Chatterjee and Strong 1984.

is the pattern to be expected from fluids containing Cl (LREE leaching) and F and CO₃ (HREE deposition). The trend is intensified in greisen (Figure 25.4).

Baker and Hellingwerf (1986) reported a systematic variation in REE through mineralized granites to W and Mo skarns in Sweden. Dennison and Ikramuddin (1986) showed variations in REE related to mineralization in syenite porphyry with related gold mineralization in the South Moccasin Mountains (Montana, U.S.A.). Altered, but unmineralized, rocks are enriched in REE relative to unaltered rocks. Mineralized syenite porphyry is depleted in HREE, may have Eu anomalies, and LREE are generally enriched relative to unaltered rocks.

LOCAL- AND MINE-SCALE EXPLORATION

The Porphyries

Most of the published case histories on local- and mine-scale exploration are for porphyry deposits. The main features of the deposits reviewed by Govett and Nichol (1979) and Govett (1983) are Cu and S anomalies and alteration zones with enhanced K and Rb, and depleted Ca and Sr. Generally, Cu, Rb, and K have peak values over the ore zone, and S has maximum values at the periphery. Other elements — notably As, Sb, Te, Au, Ag, and Mn — are useful in particular cases. Haloes are generally large (1 km), and zoning of elements is common.

Proterozoic porphyry occurrences in Finland have distinctive haloes that may be detected by samples at a density of 10 to 40 per km² (Nurmi 1984, 1985). The patterns and anomalous elements vary depending upon local conditions, but the zoning sequence is the same at all occurrences — i.e. Mo — K₂O (±Rb ±Sr ±Ba ±SiO₂) — Cu (±Sb ±As) — Zn (±Pb). The S anomalies are weak, and the

greatest anomaly contrast (4 to 7) is given by the ore elements. The more widely dispersed elements have contrasts of 2 to 3.

Some characteristic patterns for various deposits are summarized in Table 25.1. The zoning pattern for the Hall Mo deposit (Nevada, U.S.A.) is shown in Figure 25.5. Shaver (1986) pointed out that weak and sporadic anomalies for W, Bi, Nb, and low Tl for quartz monzonite-molybdenum porphyries contrast with their much stronger development at Climax-type deposits. He suggested that strong anomalies for F, Pb, Zn, Ag, Mn, and, locally, Sn are characteristic of both the quartz monzonite-type and Climax-type deposits.

Heberlein *et al.* (1983) showed that at the Berg porphyry Cu-Mo deposit (British Columbia, Canada), anomalous patterns persist from the hypogene zone to the surface leached cap, although Zn is essentially eliminated from the supergene zone and leached cap (Figure 25.6; Table 25.1). There has been considerable vertical redistribution of elements: Mo, Pb, and Ag are relatively concentrated in the leached cap compared to the hypogene zone; Zn, Cu, and Mn are depleted in the leached cap and relatively enriched in the supergene zone. Schwartz (1981) similarly concluded from studies on the La Granja porphyry copper deposit in Peru that high-grade Cu ore can be detected by high contents of K, Rb, and Mg and low contents of Sr, despite intense weathering that has given rise to a 200 m thick leached cap. Also, the distribution of Mg, Ca, Na, K, Rb, and Sr can still be correlated with different phases of hydrothermal alteration.

Other Deposits

The use of rock geochemistry for Sn exploration was investigated by Arrykul (1985) around the Taronga Deposit (New South Wales, Australia) where mineralization occurs as low-grade sheeted veins in

TABLE 25.1. CHARACTERISTIC ZONING PATTERNS AROUND SOME COPPER AND MOLYBDENUM PORPHYRY DEPOSITS. ZONING IS GIVEN FROM THE DEPOSIT OUTWARDS.

Deposit	Geochemical Zoning	Comments	Source
Hall (Nevada, U.S.) Mo, Cretaceous	Mo-Cu, Sn(W), F-As, Pb-Zn-Ag-Mn-Au	2x background F < 1 Km; Figure 25.5	Shaver (1986)
Rautio (Finland) Mo-Cu-Au, Proterozoic	Mo-As-K, Cu-Au	1 km ²	Nurmi and Isohanni (1984)
Kuukhdanaari (Finland) Mo-Cu, Proterozoic	Mo, Cu, K-Au	Mo 2km, k-Au 2 km	Nurmi (1985)
Dexing (Jiangxi, China) Mo-Cu, Jurassic	Mo-Cu, Ag-K, Rb, F	depletion of Na and Sr in k-Rb-F zone	Yu (1981)
Shanfang (Henan, China) Mo-W, Proterozoic	Mo-W-Sn-F, Cu-Zn Pb-Ag	haloes < 700 m	Zhang <i>et al.</i> (1984)
Berg (B.C., Canada) Cu-Mo, Tertiary	Cu-Mo-Ag, F, Pb-Zn	Figure 25.6 and text	Heberlein <i>et al.</i> (1983)

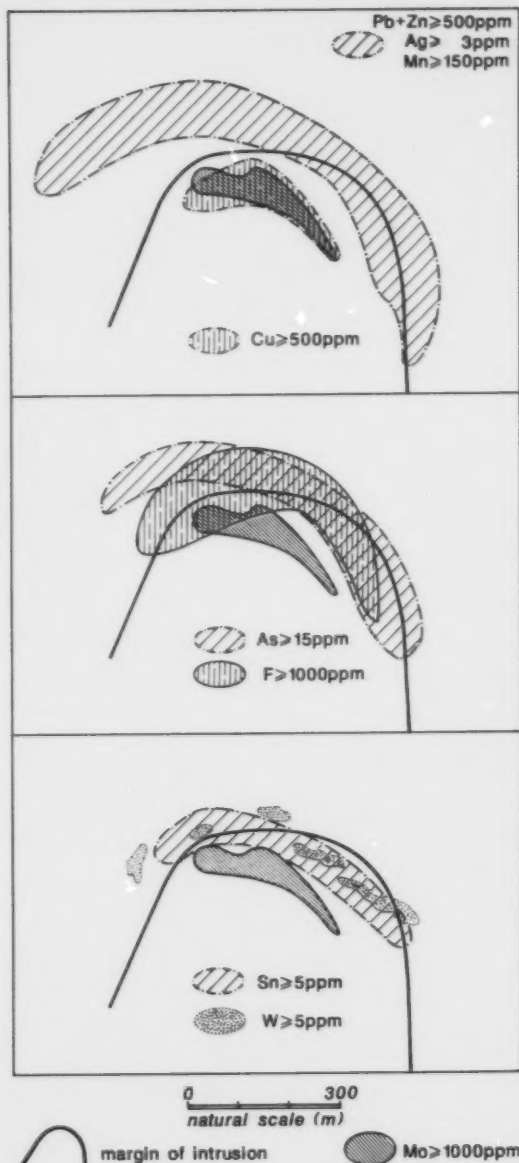


Figure 25.5. Distribution of Pb, Zn, Ag, Mn, As, F, Sn, and W around the Hall molybdenum deposit, Nevada, U.S.A. (compiled from Shaver, 1986).

hornfelsic siltstone and sandstone intruded by the Mole "tin" granite. Rock chip samples of siltstone and argillite were collected at a sample interval of 150 m along traverses 1.5 km apart over an area of about 100 km². A broad zone of more than 3 km wide and 10 km long that includes the Taronga Deposit and other smaller deposits is defined by F contents greater than 80 ppm (Arrykul *et al.*, in press). The Taronga Deposit itself is clearly defined by Sn, As, Li, and F haloes of about 1 x 2.5 km. Detailed rock chip samples taken across the deposit show

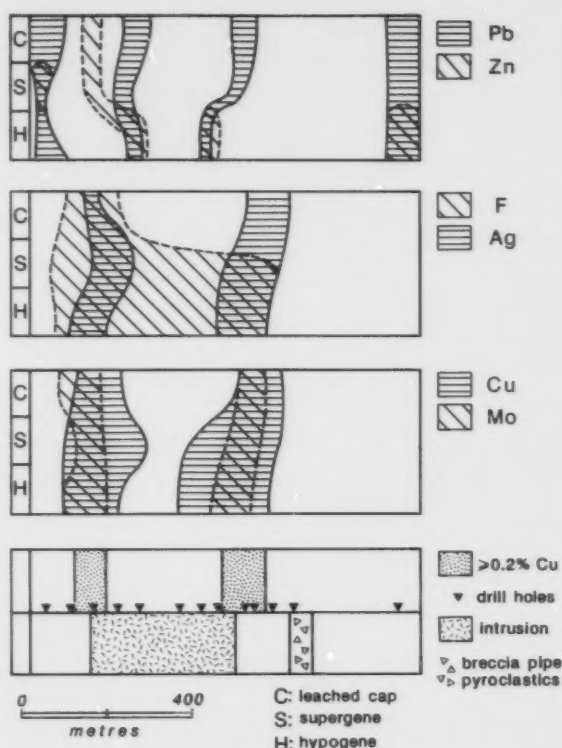


Figure 25.6. Schematic distribution of anomalous haloes of Cu, Mo, Ag, F, Pb, and Zn around the Berg porphyry Cu-Mo deposit, British Columbia, Canada (compiled from Heberlein *et al.* 1983).

strong anomalies in As, Sn, and F, and a lesser anomaly for Li. The ratios Rb:Sr, K:Na, and Mg:Ca also give strong positive anomalies (Figure 25.7).

Rock geochemistry has not been used extensively in the search for skarn and marble-hosted sulphide deposits. The genesis of the Olympias (Greece) Zn-Pb deposit in marbles is in doubt, but it is probably essentially epigenetic related to nearby granites (S.I. Kalogeropoulos, Institute of Geology and Mineral Exploration, Athens, Greece, personal communication, 1987). According to Mantzos and Hale (1986) the trace element distributions are largely controlled by the clay fraction of the carbonates. Using Zn regression residuals to eliminate the effect of clay material, dispersion haloes are recognized up to 80 m stratigraphically above and 30 m stratigraphically below the ore horizon and at least 300 m beyond the ore horizon; similar patterns are given by Mn-Zn-Pb factor scores.

Altered marbles, host to Cu-Zn-Fe-W-Mo-Bi sulphide skarns in the Gruvasen area of Sweden, are reportedly recognizable by K, Na, Sc, Rb, La, Th and Zn patterns. The Zn-Fe-Pb-As skarns are indicated by Zn, As, Pb and Sb patterns (Hellingwerf 1986).

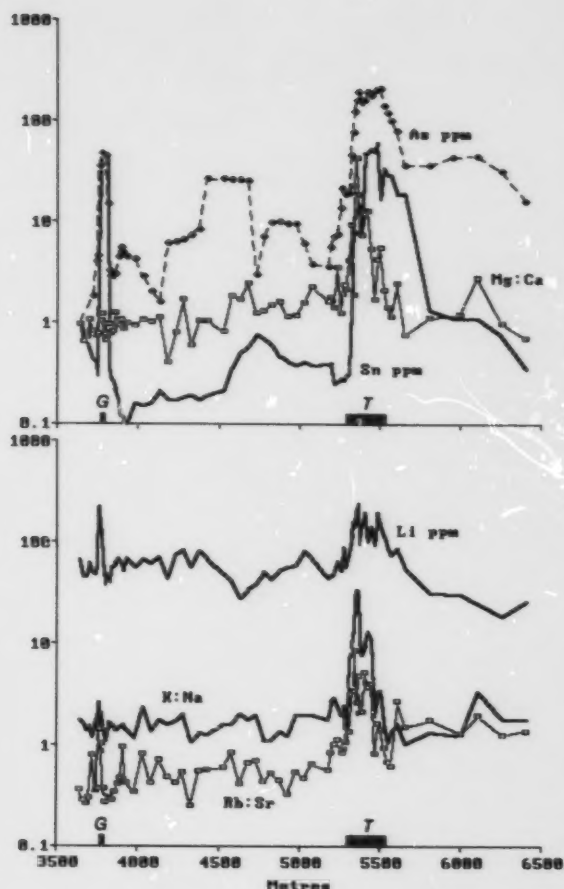


Figure 25.7. 3-point moving average of As, Sn, Li, (ppm) and ratios of Mg:Ca, K:Na, and Rb:Sr in rock chip samples across the Taronga (T) Sn deposit, New South Wales, Australia. G=Griffith's Lode prospect (compiled from Artykul 1985).

STRATIFORM DEPOSITS OF VOLCANIC AND SEDIMENTARY ASSOCIATIONS

REGIONAL-SCALE EXPLORATION

The close genetic association between exhalative sulphide deposits and their host rocks — and a relatively clear understanding of the genesis of the deposits — has led to the recognition of extensive geochemical haloes around individual deposits. However, attempts to define an association between sulphide deposits and specific volcanic associations (analogous to attempts to classify granitoids in terms of mineral potential) have not been notably successful. As was pointed out by Stanton and Ramsay (1980), pyritic Cu sulphides occur in generally mafic and tholeiitic lavas. Zinc contents increase relative to Cu in andesitic to dacitic sequences. Lead be-

comes abundant in rhyodacitic and rhyolitic sequences.

Earlier work suggested that the Zn-Cu and Zn-Pb-Cu deposits occur dominantly in calc-alkalic rocks (Sangster 1972; Descarreaux 1973; Cameron 1975). More recent work suggests that even this broad distinction is doubtful. According to Fox (1979) Kuroko-like massive sulphides can be hosted by subalkalic rocks which vary from strongly tholeiitic to strongly calc-alkalic. Sopuck *et al.* (1980) reported that felsic volcanic rocks from around Zn-Cu deposits at Uchi Lake, Sturgeon Lake, Noranda, and Normetal (in greenstone belts within the Superior Province of the Canadian Shield) straddle the tholeiitic-calc-alkalic boundary; felsic to intermediate rocks from unproductive areas are generally calc-alkalic. Both productive and non-productive rocks in a particular area may display a calc-alkalic trend — irrespective of whether they fall in the tholeiitic or calc-alkalic field.

Sopuck *et al.* (1980) drew attention to the problem of using AFM diagrams to distinguish between tholeiitic and calc-alkalic rocks in areas of massive sulphide deposits. Depletion of Fe and Mg in calc-alkalic rocks relative to tholeiitic volcanism may be obscured by the characteristic Fe and alkali metasomatism associated with massive sulphides. This is emphasized by Davies *et al.* (1979) who demonstrated the unreliability of AFM diagrams in classifying rocks from the Timmins area of Ontario. These authors showed that immobile elements (Y, Zr, Ti, Cr) are more useful. The value of Ti and Zr for determining the primary petrological character of altered and metavolcanic rocks is also demonstrated by Dudas *et al.* (1983) and Peterson (1983). It is therefore concluded that the assumption that Zn-Pb-Cu massive sulphides occur exclusively in calc-alkalic rocks cannot be substantiated.

Attempts to geochemically discriminate between productive and barren volcanic cycles within the Archean have had some success (Davenport and Nichol 1973; Nichol 1975; Sopuck *et al.* 1980). Variations in trace and major elements due to differentiation trends are likely to be more significant than small differences due to mineralization; geochemical data should, therefore, be normalized to account for differentiation.

Notwithstanding the logic — and practical success — of regressing elements against SiO_2 to compensate for fractionation effects as demonstrated by Sopuck *et al.* (1980), this approach assumes that there has been no pervasive and wide-spread silicification. Studies on the Amulet rhyolite formation at Noranda in Québec by Gibson *et al.* (1983) indicate that it is, in fact, a silicified andesite; the chemical changes are widespread addition of Si and depletion of Al, Fe, Mg, Ti, and Ca. An associated alteration type (mottled epidote-quartz) resulted in addition of Si and Ca, and depletion of Al, Fe, Mg, and Ti. There is a close spatial and temporal asso-

ciation between massive sulphide deposits in the area (Lake Dufault, Amulet orebodies, and Millenbach) and the silicified horizon. Gibson *et al.* (1983) suggested that silicification eventually sealed the upper part of a geothermal aquifer forming an impermeable caprock; later ore solutions were thus focused at a few localities in northeast- and northwest-trending synvolcanic fracture systems. The work suggests that, whereas widespread silicification may provide a large target for massive sulphides, SiO_2 may be of limited use as a guide to fractionation.

Campbell *et al.* (1982) argued that if the distinction between productive and non-productive volcanic rocks is related to the genesis of the rocks, this should be reflected in the REE geochemistry. In felsic volcanic rocks associated with massive sulphides studied in Canada, Australia, and Japan, the REEs have a characteristic flat pattern (low La:Lu ratios) and strong Eu anomalies. Barren felsic volcanic rocks show light REE enrichment, and Eu anomalies are weak or absent.

Whitford (1983) suggested that flat REE patterns with large Eu anomalies are more likely to arise from alteration processes rather than being primary features of felsic rocks. Campbell *et al.* (1984) showed that there is little evidence of REE mobility in pervasively altered rocks around the South Bay, Mattabi, and Kidd Creek Mines in Ontario. REEs are mobile, however, in the alteration pipes below the deposits, and there is fractionation of light and medium REEs from heavy REEs. The authors tentatively suggested that the degree of mobility is approximately proportional to the size of the deposit.

There are only a few descriptions of regional-scale surveys (i.e. a few samples over a wide area). The survey of the Troodos volcanic series on Cyprus (Govett and Pantazis 1971; Govett 1972) has been reviewed by Govett and Nichol (1979) and Govett (1983). The survey over 2 000 km^2 of northern New Brunswick, Canada based on one rhyolite sample/5 km^2 (Govett and Pwa 1981) gave results similar to those for Cyprus, insofar as the massive sulphide deposits are confined to areas depleted in Cu.

Soviet literature (e.g. Ovchinnikov and Baranov 1972; Beus and Grigoryan 1977) advocates analysis of heavy mineral separates to enhance the extent and intensity of anomalies. Allen and Nichol (1984) used this approach with felsic volcanic rocks around the South Bay massive sulphide deposits. On the basis of four samples/ km^2 they demonstrate a Cu-Pb-Zn-Ag anomaly up to 10 km along strike; whole rock anomalies extend only 1 to 2 km from the deposit (Figure 25.8). It is suggested that similar results could have been obtained with a sulphide-selective leach as used by Cameron *et al.* (1971) to discriminate between Ni-mineralized and barren ultramafic intrusions.

Selinus (1983) derived a multi-element discriminant score halo of 1 x 25 km outlining the ore zone in the Precambrian Stollberg ore zone in central Sweden which has magnetite iron ores (with galena and sphalerite) and Pb-Zn-Ag sulphide ores. Möller *et al.* (1983) sampled a 36 km traverse along the northern flank of the Rio Tinto Syncline (Spain) with an average sample interval of 1.5 km. Enhanced levels of As, Sb, Tl, and F and reduced contents of Na in exhalative Fe-Mn slates stratigraphically above or equivalent to sulphide bodies indicate the main Mn-rich occurrences and some sulphide bodies. These same elements in the volcanic rocks that are host to sulphide deposits are anomalous around sulphide bodies. The overlying slates and greywackes have low-contrast anomalies.

A number of studies indicate that sedimentary and exhalative horizons stratigraphically close to the ore horizon generally exhibit extensive anomalies (Russell 1974; Coope 1977; Gwosdz and Krebs 1977; Coope and Davidson 1979). Scott *et al.* (1983) stated that ferruginous chert, cherty tuff, and sulphide iron formations (which they referred to as

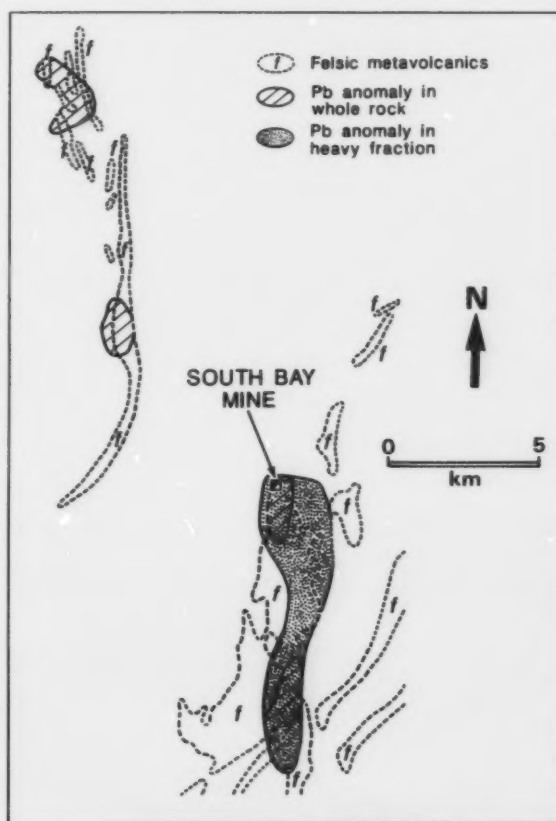


Figure 25.8. Distribution of anomalous contents of Pb in the heavy mineral fraction and whole rock of felsic volcanic rocks around the South Bay massive sulphide deposit, Ontario, Canada (compiled from Allen and Nichol 1984).

"tuffaceous exhalite") show variations in chlorite composition, alteration of ilmenite, and Mn content related to massive sulphides. Variations in trace elements are erratic and inconsistent from deposit to deposit.

LOCAL- AND MINE-SCALE EXPLORATION

Govett and Nichol (1979) and Govett (1983) reached the following conclusions from reviews of the very large number of case histories of deposits ranging in age from Archean to Tertiary in Canada, Australia, Japan, Europe, Cyprus, Turkey, and Fiji:

- The responses are remarkably consistent, irrespective of age and location.
- Aureoles are extensive (500 m or more stratigraphically vertically and 1 to 2 km laterally).
- Footwall anomalies, especially around proximal deposits, are more intense than hanging wall anomalies; significant hanging wall anomalies seem to be absent in Archean deposits.
- Cu may be enriched in the footwall and depleted in the hanging wall; Mn tends to show the reverse behaviour.
- Both K and Mn may be relatively depleted close to the ore zone and enriched further away.
- Fe and Mg are enriched, and Na and Ca are depleted in nearly all cases. Exceptions are mostly due to differences in ore composition and to variations in lava fractionation, texture of rock, and sediment:lava ratios, whether deposits are proximal or distal.
- The ore elements, especially Zn, are commonly enriched. In some cases Cu is depleted, except in the immediate wall rocks.

Subsequent work has generally confirmed these conclusions (Table 25.2). A compilation of element response from published data (Table 25.3) shows that in more than 85 percent of the cases Zn, Pb, Fe, Mn, and Mg are enriched, and Ni, Na, and Ca are depleted.

Anomalous behaviour for a number of other elements in particular cases are:

- P enrichment at the Heath Steele Deposits in New Brunswick, Canada (Wahl 1978) and Kangasjärvi, Finland (Rehtijärvi 1984a), and P depletion at Lampinsaari, Finland (Rehtijärvi 1984a)
- Cl and B enrichment in serpentinite beneath the Outokumpu Cu-Co deposit in Finland (Rehtijärvi 1984b)
- Bi, Sb, Se, and As enrichment at Avoca, Ireland (Moon and Hale 1983)
- Au enrichment at Mount Morgan, Queensland, Australia (Fedikow and Govett 1985)

- Ba enrichment at Pinnacles, New South Wales, Australia (Rugless and Govett 1984)

Regression against SiO_2 to eliminate variations in other elements due to fractionation assumes that SiO_2 itself is not a significant component of alteration — which Gibson *et al.* (1983) demonstrated is not the case in their regional study around Noranda (see above). Lavery (1985) investigated this problem at the Precambrian Crandon massive sulphide deposit (Wisconsin, U.S.A.). The 70 million tonne Zn-Cu deposit is within greenschist metamorphosed tuffs of a subalkalic intermediate to felsic volcanic sequence. There is marked depletion of Na transecting all texturally defined stratigraphic contacts and extending 360 m into the stratigraphic footwall and at least 220 m into the stratigraphic hanging wall (Figure 25.9). There is no distinctive pattern in the distribution of SiO_2 . The contents of Zr and TiO_2 show little difference between the rocks at the deposit and those more distant, and these elements are therefore assumed to have been relatively immobile during alteration processes.

Lavery (1985) regressed SiO_2 against Zr/TiO_2 ratios for 496 analyses of subalkalic volcanic rocks from the Abitibi Subprovince published by Goodwin (1979). Results from calculations of the predicted SiO_2 for the Zr/TiO_2 ratios around the deposit show that the deposit lies near the top of an andesitic sequence overlain by dacite. The distribution of SiO_2 residuals (analytical-predicted) gives a strong halo of SiO_2 enrichment around the deposit (Figure 25.9); at least 7.4 percent SiO_2 has been added to the rocks beneath and along strike from the deposit.

Based on studies at the Boto massive sulphide prospect in rhyodacitic tuffs (near Mount Chalmers, Queensland, Australia) Taylor *et al.* (1984) suggested that elements that had been mobile due to alteration processes could be identified by the degree of variance from a log element/ TiO_2 versus log Zr/TiO_2 . They deduced that Ca, Na and, significantly, Si contents in hanging wall tuffs were modified by post-mineralization hydrothermal activity.

There have been a number of studies on sediment-hosted stratiform sulphide deposits; haloes are commonly extensive (Table 25.2). Smee and Bailes (1986) derived some interesting geochemical guides to ore around the South Zone of the Jason Pb-Zn-Ag deposit within Middle to Upper Devonian shales and turbidites 400 km northeast of Whitehorse in the Yukon. A high-grade massive sulphide is interpreted as being proximal to the vent and grades to a chert-barite facies to the west. Altered rocks (silicified and carbonitized) occur in the footwall and are most intensely altered below the thickest and highest-grade part of the massive sulphides around Drill Hole 56B (Figure 25.10). The $\text{Pb}:(\text{Pb}+\text{Zn})$ ratios in the upper layer of the sulphides increase towards the zone of most intense alteration, i.e. towards the presumed source of hydrothermal solutions. The distribution of As and Cu

TABLE 25.2. SUMMARY OF LOCAL-SCALE GEOCHEMICAL RESPONSES IN BEDROCK AROUND SOME VOLCANIC- AND SEDIMENT-HOSTED MASSIVE SULPHIDE DEPOSITS FROM RECENT LITERATURE. (SEE GOVETT 1983 FOR SUMMARY OF LITERATURE TO 1981).

Deposit	Anomalous elements	Comments	Source
Volcanic hosted			
Jones Hill (New Mexico, U.S.), Proterozoic	+Mg, Fe, Mn, Cu, Pb, Zn As, -Na, Ca, Sr	300 m around deposit	Peterson (1983)
Condor (Yellowknife, Canada), Archean	+Mg -Na		Bubar and Heslop (1985)
Lyon Lake (Ontario, Canada), Archean	+Cu, Zn, Fe, Mn, Ca, Mg -Na, K		Harvey and Hinzer (1981)
23 deposits, Abitibi Belt (Québec, Canada), Archean	+Mg -Na, Ca	<1 km diameter	Marcotte and David (1981)
Stirling Hill-Pinnacles (N.S.W., Australia), Archean	+Cu, Zn, Fe, K, Rb -Ba, Na, Sr, Pb		Rugless and Govett (1984)
Joutel, Poirier, E. Waite, Mattabi (Superior Province, Canada), Archean	+Fe, Mg (Zn, Ag) -Na, Ca	typically proximal	Amor and Nichol (1983)
South Bay, Sturgeon Lake, Mobrun, Mattabi, E. Waite (Superior Province, Canada), Archean	+K -Na, Fe, P, Mg		Amor and Nichol (1983)
Crandon (Wisconsin, U.S.), Precambrian	+SiO ₂ -Na	Figure 25.10 and text	Lavery (1985)
Sediment hosted			
Lady Loretta (Queensland, Australia), Proterozoic	+Zn (Hg, Pb, Ag, Ba)	50 m HW, 100m FW, 1.5 km lateral	Carr (1984)
Green Mountain (Calif. U.S.), Jurassic	+Mg -Na	FW	Mattinen and Bennett (1986)
Howard's Pass (Yukon, Canada), Silurian	+Zn, Pb, Hg, Ca in FW +Cu, Ni, Co, Mo, Sb, As, Fe lateral	Same elements anomalous in Devonian due to reactivation of hydrothermal activity	Goodfellow <i>et al.</i> (1983)
Tom (Yukon, Canada), Silurian	+Zn, Ba	Zn, 3.5 km	Large (1981)
Jason (Yukon, Canada), Silurian	Cu, As, Mn	Figure 25.11 and text	Smee and Bailes (1986)

in footwall rocks substantiate the interpretation of a source vent in the vicinity of Drill Hole 56B. The distribution of Mn in the hanging wall rocks shows an elongated zone of relatively low Mn parallel to the footwall Cu anomaly (Figure 25.10). Low Mn in the vicinity of source areas for sulphide deposition due to acid and reducing conditions has been noted around many other deposits (Govett 1983).

According to Smee and Bailes (1986) anomalous Ba is indicative of hydrothermal activity and is a typical component of a distal brine pool. Enrichment in post-ore hanging wall rocks above a brine pool would be largely diffusion-controlled. The Ba con-

tent of the first 10 m of the hanging wall at the Jason Deposit increases to the west and with depth, indicating that brine probably flowed east to west. The Ba content as a function of distance into the hanging wall shows typical diffusion-type decay curves in Drill Holes 63 and 68 (Figure 25.10). The stronger driving force is clearly in Drill Hole 68 — which is where the Ba content is highest. The decay curve for Drill Hole 56B is not exponential, which suggests that diffusion was increased by a factor other than chemical gradient. As Drill Hole 56B is in the vicinity of the presumed hydrothermal source, the additional driving force was probably heat. The rate of change of concentration (Δc) over the first 10 m

TABLE 25.3. SUMMARY OF LOCAL AND MINE SCALE GEOCHEMICAL RESPONSE FOR SOME ELEMENTS IN HOST ROCKS AROUND MASSIVE SULPHIDE DEPOSITS IN AUSTRALASIA, EUROPE, AND NORTH AMERICA.

	Number of cases	% of cases		
		Enrichment	Depletion	Variable
Cu	18	61	28	11
Pb	13	92	8	-
Zn	29	93	7	-
Ni	7	-	100	-
Co	10	80	20	-
Fe	27	96	-	4
Mn	20	85	-	15
Na	33	6	94	-
K	16	44	38	18
Ca	25	4	92	4
Mg	32	88	12	-

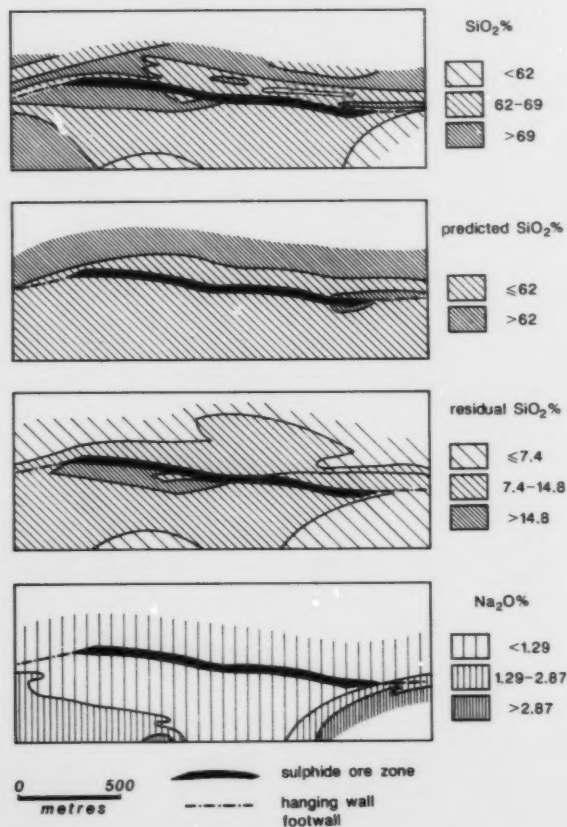


Figure 25.9. Distribution of Na_2O , and actual, predicted, and residual SiO_2 around the Crandon Zn-Cu massive sulphide deposit, Wisconsin, U.S.A. (compiled from Lavery 1985).

(Δd) of hanging wall shows that the greatest rate of change occurs in the west (Figure 25.10) — which again indicates a brine source to the east.

VEIN AND REPLACEMENT DEPOSITS

Vein-type deposits — generally linear fault, fracture, and fissure-filled deposits — represent the smallest exploration targets. Geochemical haloes around discrete mineralized bodies are generally narrow, although they are well-defined due to strong wall rock-alteration from the introduction of hydrothermal solutions.

Vein-type and replacement deposits closely associated with plutonic rocks or large hydrothermal systems are likely to have a regional-scale geochemical response. In general, large mineralized districts will have more extensive anomalies than smaller mineralized districts. Deposits that are less closely related to intrusions, and where there is no significant regional alteration, may have regional-scale anomalies detectable in samples of the hydrothermal plumbing system — fracture fillings and vein material — rather than in whole rock (Govett 1983).

Logarithmic-decay-type dispersion patterns in wall rock directly related to individual veins or ore-shoots consistently extend for 20 to 40 m from the ore (although impermeable wall rock or reactive carbonate wall rock may cause narrower dispersion patterns). This is true for precious metals (e.g. Bolter and Al-Shaieb 1971), and for base metals (e.g. Lahti and Govett 1981).

A few detailed systematic studies indicate that rock geochemistry can assist in locating ore shoots in vein-type workings. Barnes and Lavery (1977) showed that Zn decay patterns (corrected for background alumino-silicate Zn) in carbonate rocks in the Wisconsin (U.S.A.) lead-zinc district could be related to the thickness of the vein and the distance

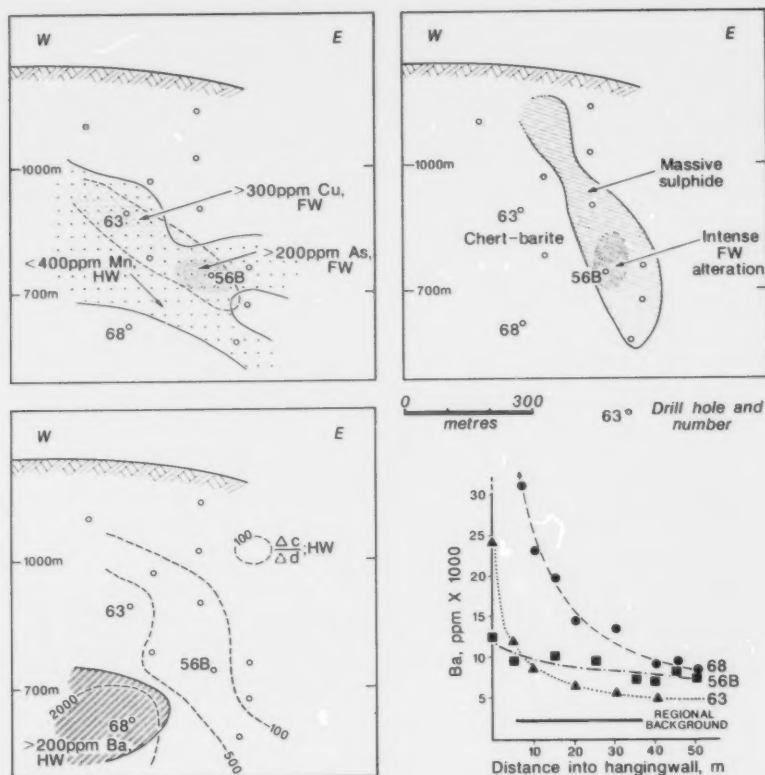


Figure 25.10. Geochemistry of South Zone of the Jason Pb-Zn-Ag deposit, Yukon, Canada. Top right: longitudinal section showing main mineral facies. Top left: distribution of Mn in hanging wall (HW), and As and Cu (first 20 m) in footwall (FW). Bottom right: variation of Ba concentration with distance in hanging wall. Bottom left: distribution of Ba and rate of change in Ba concentration in first 10 m of hanging wall (compiled from Smea and Bailes 1986).

from the vein. Sinclair and Tessari (1981) established a useful zoning sequence in quartzite interbedded with schist and phyllite around the Keno Hill (Yukon) Ag-Pb-Zn vein deposits based on analyses of 23 elements in samples taken at an average of 3 m intervals across several Ag ore shoots and barren ground. Linear correlation identified five groups with good intra-group but poor inter-group correlation:

- Group I: Pb, Bi, Sb, Cu, Ag (galena-freibergite)
- Group II: Zn, Cd, Hg (sphalerite)
- Group III: Ca, Sr, Mg (calcite or dolomite)
- Group IV: Fe, Mn, Ni (pyrite-siderite)
- Group V: Fe, B, V, Ba (probably tourmaline, barite and rutile).

Ore shoots occur within rocks with high contents of Ag. Therefore all samples were rearranged in order of decreasing Ag content. Smoothing of data by a cubic spline function showed a clear zonation around an ideal ore shoot of Groups I, II and III (Figure 25.11). The pyrite halo can be detected by measurement of Co (Fe cannot be used because of the presence of siderite). Ratios of Co to Ag give a

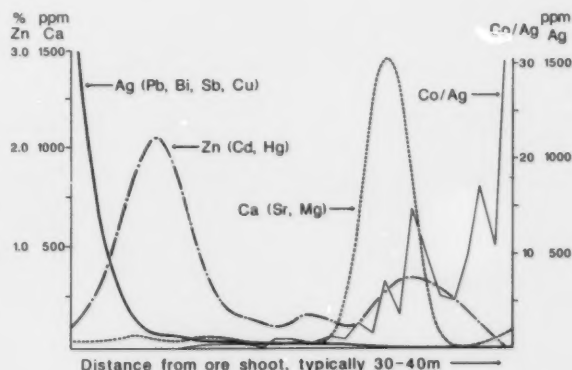


Figure 25.11. Characteristic haloes around idealized Ag-Pb-Zn vein at Keno Hill, Yukon, Canada (compiled from Sinclair and Tessari 1981).

well-defined pattern of decreasing values towards mineralization (Figure 25.11). The ideal zonation occurs around ore shoots varying in size from 3 to 90 m.

NEW DEVELOPMENTS — GOLD

Some of the more comprehensive review-type publications on precious metals in general are: Boyle (1979), Levinson (1982), Hodder and Petruk (1982), Colvine (1983), Foster (1984), Berger and Bethke (1985) and Tooker (1985). There has been an enormous volume of published work on the geology and geochemistry of gold during the past decade. Fast flameless AAS techniques for low ppb level Au have dramatically changed the approach to geochemical exploration for Au in all media. Although trace element pathfinders are also increasingly used, there is no longer the total reliance on them (especially As) that characterized work in the 1950s to 1970s. There is still widespread concern for the sample and sub-sample size requirements for reliable Au analyses (Clifton *et al.* 1969; Gy 1979; Harris 1982; Nichol 1986). Whereas reliably large samples are essential for ore assays, it is the opinion of the writer that in most circumstances an adequate level of low micron-size Au exists to detect ppb geochemical haloes with small samples.

DEPOSITIONAL CONTROLS AND GEOCHEMICAL FEATURES

The aqueous chemistry of Au is now reasonably well understood, and it is generally agreed that HS^- and Cl^- are the most important ligands for the transportation of Au (Henley 1973; Seward 1973, 1979; Cole and Drummond 1986). Epithermal gold deposits are interpreted within the framework of geothermal systems (Henley and Ellis 1983). Boiling is regarded as the most significant factor causing deposition of Au — either directly or through ex-solution of CO_2 and H_2S (Cole and Drummond 1986). Partition of dissolved gases to steam phases, and possible oxidation leading to an acid condensate above the boiling zone, may be expected to cause SiO_2 deposition on the boundaries of geothermal systems. Mineralogical changes should include the growth of K-feldspar, mica, and deposition of quartz (Henley and Ellis 1983).

A significant observation by Seward (1984) was that amorphous Sb and As sulphide sols are efficient absorbants of Au from aqueous solutions. Berger and Silberman (1985) suggested that the permeability of host rocks is one of the most important controls. Henley and Ellis (1983) concluded that although the original rock composition influences the secondary mineralogy, it is less important than permeability, temperature, and fluid composition; indeed, Henley (1985) stated that unusual Au con-

tents of the source rock are less important for the formation of an economic deposit than the hydrology and chemistry of the system.

In modern geothermal systems — such as those at Steamboat Springs (Nevada, U.S.A.) and Broadlands (New Zealand) — a distinct vertical geochemical zoning was identified by Silberman and Berger (1985) and Ewers and Keays (1977) as follows:

- Upper: Au, As, Sb, Hg, B, Tl
- Lower: Cu, Pb, Zn, Bi, Se, Te, Co, Ag

Thus, epithermal gold deposits should be expected to have associated haloes of some or all of the above elements (depending upon the part of the system examined). Alteration processes could also lead to loss from the host rocks of Na (and possibly Ca) and gains in K and SiO_2 .

Lode gold deposits occur in quartz veins, as stratiform horizons, and as stockworks in felsic intrusive rocks in Archean terrain. Common regional associations in the Superior Province of Canada are a dominance of mafic rocks, often with an ultramafic (komatiitic) component; major sedimentary sequences; and a low ratio of felsic to mafic rocks. On a mine scale there is normally a closely associated felsic intrusive or extrusive association (Hodgson *et al.* 1982). The role of ultrabasic rocks in general, and komatiites in particular, as source rocks especially enriched in Au is in dispute. Keays (1984) argued persuasively that komatiitic and related magmas are enriched in precious metals. Kerrich and Fryer (1979) denied that they are enriched in Au. Specific studies indicate that there is no analytical evidence for significant enrichment of Au in any particular rock type (Kwong and Crocket 1978; Saager *et al.* 1982).

On an empirical basis Archean gold deposits are regionally associated with carbonatization; more local-scale alteration is sericitization, silicification, and sulphidization. According to Kerrich and Hodder (1982) alteration is characteristically reflected by addition of K and associated alkali metals, CO_2 and SiO_2 (and in some cases Fe, Mg), and loss of Na. Trace elements that are commonly associated with Au include As, Sb, Bi, W, B, Mo, Ba, and Cr. The geochemical signatures for Archean metamorphic deposits are, therefore, similar to those for epithermal, more recent deposits.

REGIONAL AND LOCAL-SCALE EXPLORATION

In the examples below, "regional-scale" implies anomalous responses of >1 km or several km^2 ; deposit-scale is restricted to responses of a maximum several hundred metres. This terminology follows literature usage for gold deposits (both types would be considered as local- and mine-scale in the terminology adopted for plutonic and volcanic deposits above).

Archean

Carbonate alteration is a characteristic feature of many gold-mineralized areas, but Davies *et al.* (1982) pointed out that the CO₂ content of altered rocks merely measures the amount of carbonate present and gives no indication of the intensity of alteration. They derived a series of relations for the CO₂:CaO molar ratios for the Timmins area of Ontario that show the following, in order of increasing CO₂ metasomatism:

- CO₂:CaO < 1 only calcite present
- CO₂:CaO = 1 mostly calcite, minor dolomite or ankerite
- CO₂:CaO = 1–2 calcite with ankerite or dolomite
- CO₂:CaO = 2 dolomite (ankerite) only

The mean CO₂:CaO ratio in the Timmins area is 0.67 compared with 0.13 in nearby unmineralized areas; corresponding As contents are 4 ppm and

0.35 ppm. They suggested that large areas (several km²) with CO₂:CaO ratios close to one and As > 1 ppm can be identified as targets for follow-up exploration based on a sample density of 10/km². On a local scale (samples at <150 m interval) anomalous targets would be identified by various combinations of the following anomalies: CO₂:CaO > 1.5, As > 10 ppm, K₂O > 0.75 percent.

The geochemical responses for Archean deposits are summarized in Table 25.4. Regional-scale major element responses to Archean deposits in metavolcanic (dominantly mafic) rocks are typically gains in Si and K, and losses of Na and Ca. Trace element haloes include the elements characteristic of young epithermal deposits — As, Sb, Bi, W — as well as base metals and S in some cases. Where Au has been determined, it gives regional-scale ppb anomalies. Anomalies in stratiform exhalative deposits are generally the most extensive (e.g. the Madsen and Starrett-Olsen mines in Ontario). Deposit-scale re-

TABLE 25.4. CHARACTERISTIC GEOCHEMICAL RESPONSES FOR SOME GOLD DEPOSITS

Deposit	Anomalous elements	Comments	Source
ARCHEAN			
Eastern Red Lake area (Ontario, Canada)	+SiO ₂ , CO ₂ , K, As, Sb -Fe, Mg, Ca, Na, Sr	pervasive alteration several km ²	Platz (1982)
Campbell Red Lake, Dickenson (Ontario, Canada)	+SiO ₂ , Au, As -Na, Ca, (Mg, Fe, K) peraluminosity index: (mole % Al ₂ O ₃ /CaO+Na ₂ O+K ₂ O)>2 dolomite-ferrodolomite veinlets	anomaly 1x2 km	MacGeehan <i>et al.</i> (1982)
Madsen, Starrett-Olsen (Ontario, Canada) Madsen ore zone	+K -Na, low CO ₂ +Au, As, S, Sb, Bi	9 km in tuff, 600 m FW 200 m HW Au (1 km), As and S (2 km), a few 10s m in HW and FW Sb and B 3 km, 500 m FW, 200 m HW	Durocher (1983)
Timmins area (Ontario, Canada), cherty dolomitic deposits	+Au, Sb, (As, Bi, Li, Cu, Pb)	deposit-scale	Fyon and Crocket (1982)
Bousquet (Quebec, Canada)	+K, Si, -Na, Ca +K, Si, Rb, -Na, Ca, Sr	FW tuff 70 perpendicular to deposit	Valliant <i>et al.</i> (1982)
Doyan (Quebec, Canada)	+K, -Na, Ca +S	300–500 m >3400 m x 150–300 m	Guha <i>et al.</i> (1982)
Big Bell (W.A., Australia)	+K, -Na (+S, Bi, Ba, Mo, Ag, Sb, As, W, base metals)	120 m FW, 10–30 m HW	Chown <i>et al.</i> (1984)
POST-PRECAMBRIAN			
Round Mountain (Nevada, U.S.A.)	+Au, As, Ti, Sb, Ag, Mo, W, Hg -Ca, Mn	Au largest, >1 km; Figure 25.13	Berger and Silberman (1985)
Cinola (B.C., Canada)	+Au, W +Hg, Sb +Ag	1 x 3 km for Au >500 ppb, W >23 ppm 0.8 x 2.25 km 0.4 x 1.1 km (limit of deposit)	Champigny and Sinclair (1982a, b)

sponses involve the same elements as those for regional scale (Fyon and Crocket 1982).

At the Paddington Deposit at Kalgoorlie in Western Australia, G. Booth (Ph.D. candidate, Department of Applied Geology, University of New South Wales, Sydney, personal communication, 1986) found prominent haloes of As, Sb, Te, and W related to arsenopyrite, pyrite, and scheelite associated with Au. Smaller haloes of Pb, Zn, Cu and Ag, are related to sporadic galena, sphalerite, chalcopyrite, and lesser free silver occurring as separate constituents or as inclusions in the main sulphide phases. In some sections there is a weak Tl anomaly. The haloes generally extend tens of metres from the ore zone.

Post-Precambrian

At the Round Mountain gold deposit in Nevada — a fairly typical hot spring type deposit in rhyolitic ash flow tuffs — the mineralization is associated with silicification and pervasive phyllic–argillic alteration

(Berger and Silberman 1985). The pervasively altered area has >0.05 ppm Au, depleted Ca and Mn, and anomalous As, Sb, Tl, Ag, Mo, W, and Hg (Figure 25.12, Table 25.4). The contents of As, Sb, and Tl decrease with depth. The spatially largest anomaly (>1 km) is given by Au contents >50 ppb. Similarly, Au gives the largest anomaly at the Carlin-type Tertiary age Cinola gold deposit in British Columbia (Table 25.4).

The Cu and precious metal deposits of the Copper Canyon area in Nevada occur as contact-metasomatic, skarn, and replacement and disseminated deposits in Paleozoic sedimentary rocks. The deposits are genetically related to a middle-Tertiary granodiorite porphyry. Recent work by Theodore *et al.* (1986) showed that the Tomboy–Minnie and Independence Au–Ag deposits (Figure 25.13) are part of the same system. The Cu ores of the West and East ore bodies are essentially within a zone of K-alteration; all deposits lie within a large halo of high-salinity fluid inclusions and are associated with a py-

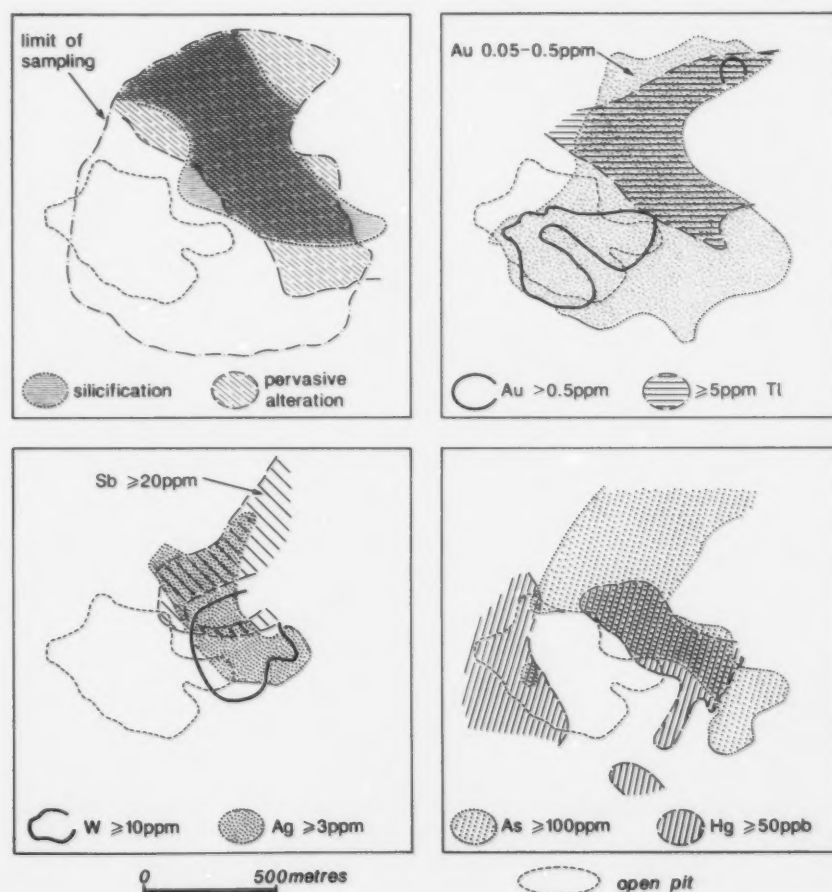


Figure 25.12. Alteration patterns, distribution of Au, Ag, Tl, W, Sb, As, and Hg in bedrock at Round Mountain, Nevada, U.S.A. (compiled from Berger and Silberman 1985).

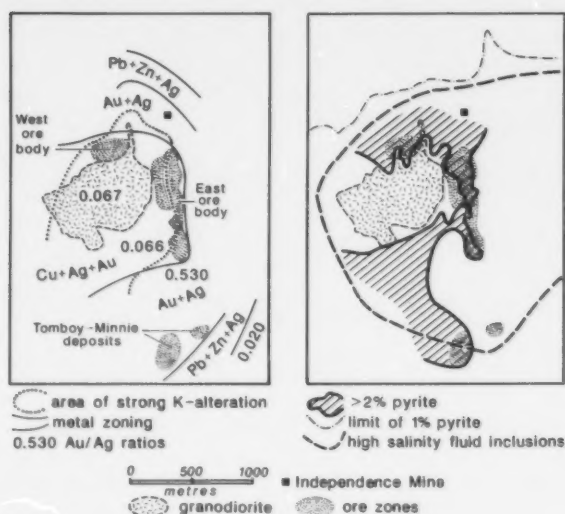


Figure 25.13. Distribution of pyrite, K-alteration, high salinity fluid inclusion haloes, metal zoning, and Au/Ag ratios in the Copper Canyon area, Nevada, U.S.A. (compiled from Nash and Theodore 1971; Theodore and Nash 1973; Theodore et al. 1986).

rite halo. Metal zoning is strongly developed from Cu-Ag-Au centred on the granodiorite, outwards to an Au-Ag zone and a Pb-Zn-Ag zone furthest away from the granodiorite; each zone has a characteristic Au/Ag ratio.

At the Pinson mine in Nevada, where gold mineralization occurs in jasperoid (which replaces Palaeozoic limestone units) along a 10 to 20 m wide fault zone, Crone *et al.* (1984) extended the technique of sampling material in joints and fractures as representative of the plumbing system by analyzing the Fe-oxide coatings. The elements Au, Hg, As, and Sb are enriched in fracture-coatings compared with whole rock. All elements for both rock chips and fracture-coatings form a halo around the gold deposit, and in both sample types the dimensions of the anomaly increase $Au < Sb < Hg < As$. As the results for Au, As, and Sb in Figure 25.14 indicate, the size of the anomalies is considerably larger in the fracture-coatings.

Restricted wall rock anomalies of the typical diffusion-controlled logarithmic decay type are described by Gresens *et al.* (1982) around silica-carbonate gold veins in serpentinite in the Blewett Mining District (Washington, U.S.A.). Pb and Zn anomalies extend 5 to 10 m from the veins, and Li for about 25 m. Ni shows increasing depletion towards the veins over a distance of more than 45 m. Govett *et al.* (1984) described bromine-soluble Te-Bi-As-Sb anomalies in Paleozoic andesitic tuffaceous rocks for up to 100 m around the London-Victoria lode Au deposit at Parkes (NSW, Australia). Ikramuddin *et al.* (1983) and Ikramuddin

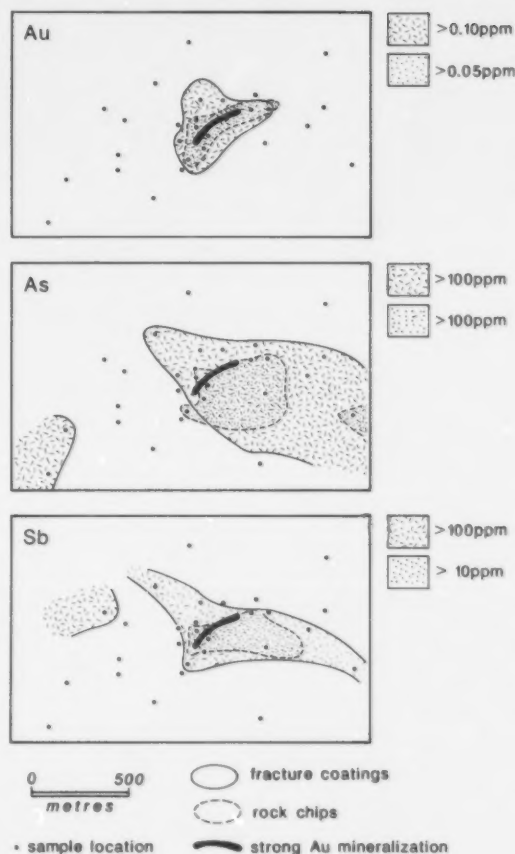


Figure 25.14. Distribution of Au, As, and Sb in rock chips and fracture coatings around the Pinson Mine, Nevada, U.S.A. (compiled from Crone *et al.* 1984).

(1986), and Massa and Ikramuddin (1986) found that Tl is generally enriched in mineralized rocks associated with gold mineralization and advocated the use of ratios of Tl with K, Ba, and Sr. Unfortunately, the scale over which these relations may be used is not clear; one specific case illustrated for the Como area in Nevada showed an anomaly over 3 m.

Use of Isotopes and Fluid Inclusions

Analysis of hydrothermal minerals and fluid inclusions for $^{18}O:^{16}O$ and D:H isotope ratios is widely used to provide data on temperature and attainment of equilibrium, and especially to determine the origin of H_2O involved in ore deposition (e.g. Kerrich and Fryer 1979). A comprehensive review by Taylor (1974) indicated that ore deposits occur in extensive areas of low ^{18}O altered volcanic rocks at the Tonopah, Goldfield, and Comstock Lode districts of Nevada. At the Tonopah Au-Ag mining district, the $\delta^{18}O = 0$ contour forms a halo of about 1.7 x 3.0 km around the district (Figure 25. 15). The lowest $\delta^{18}O$ values coincide with the apex of the productive ore zone. Taylor (1974) concluded that the

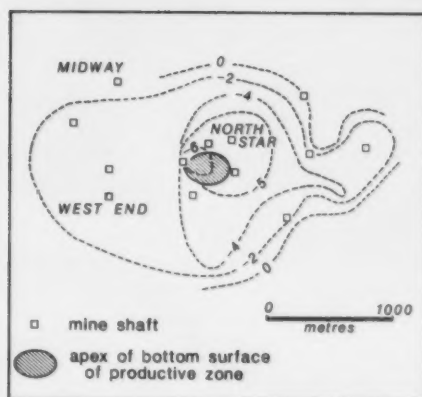


Figure 25.15. Distribution of $\delta^{18}\text{O}$ in volcanic rock, Tonopah Mining District, Nevada, U.S.A. (compiled from Taylor 1974).

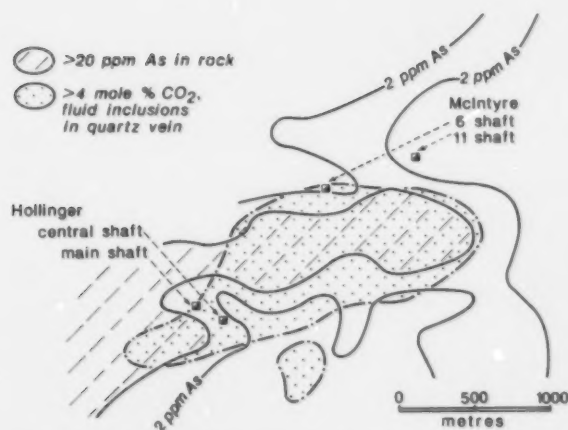


Figure 25.16. Distributions of CO_2 in quartz vein fluid inclusions, and As in whole rock around the Hollinger-McIntyre gold mines, Ontario, Canada (compiled from Smith and Kessler 1985).

lowest $\delta^{18}\text{O}$ values correspond with the zone of highest temperatures and/or where most H_2O circulated during ore deposition. Masterson and Kyle (1984) used $\delta^{18}\text{O}$ contents of vein quartz to indicate the probable source area of mineralizing ore fluids in the Velvet gold district of Nevada.

Clearly, $\delta^{18}\text{O}$ can be used to identify zones of hydrothermal alteration and to determine the likely focus of hydrothermal fluids. The greatest potential use is probably in epithermal systems, but the cost of analysis could severely limit its application; Taylor (1974) indicated an analytical production of only 100 samples/month.

Roedder (1984), in a comprehensive review of the use of fluid inclusions for gold exploration, stated that they could be used for determination of temperatures to provide evidence of boiling, and for measurement of thermal gradients to indicate source of hydrothermal solutions and compositional differences between barren and gold-bearing quartz veins. Smith and Kesler (1985) used fluid inclusions more directly at the Hollinger-McIntyre quartz-carbonate deposits in Ontario. They showed that the main mineralized zone is defined by fluid inclusions in vein quartz that contain more than four mole percent CO_2 (Figure 25.16). In whole rock As, Ba, Au, Sb and Rb are also anomalous around the deposits. The 20 ppm contour for As outlines the main area of mineralization.

SOVIET GEOCHEMISTRY

Govett and Nichol (1979) found that the results published by geochemists in the USSR — indicating that they could detect blind orebodies at depths of hundreds of metres and assess whether the haloes reflect probable economic mineralization — were difficult to evaluate. A team of geochemists from CSIRO (Australia) recently visited the USSR and produced a detailed report on Soviet geochemistry (Binns *et al.* 1987). The following is derived from their report.

Over the past 40 years the Institute of Mineralogy, Geochemistry and Crystallography of Rare Elements in Moscow collected 500 million samples, investigated 1500 anomalies, and found 150 mineral deposits (not all of which are economic). This involved 10 000 workers. They still use spark-source optical emission spectrometry because of its low cost and the need to maintain compatibility with previous data; 40 elements are determined, but many are below detection limits.

Soviet geochemists in general have made considerable efforts to use regional surveys to detect prospective terrain. They have had some success but at costs that would be excessive in Australia. On a local scale their success is no greater than in Australia.

The techniques of multiplicative and additive haloes, and vertical zonality (as described by Beus and Grigoryan 1977) are used mostly on sub-vertical epigenetic polymetallic sulphide veins, Sn-W ores in greisen, and in skarn environments. The haloes and zonality are probably due to minor ore veinlets within the samples of wall rock. Thus, the haloes reflect structural and mineralogical variations of the actual mineralized system and are not geochemical haloes as understood in the western world. Several levels of intersection are required to determine whether haloes represent potential mineralization, and apparently potential ore zonality is recognized only if reasonable ore is intersected. The detail required to determine lateral patterns to predict ore type and grade would be considered essen-

tially part of a feasibility study in Australia. The methods have been tried on flat-lying deposits and on what are probably exhalative sulphide deposits, but they have been largely unsuccessful.

Although a wide range of elements is determined, the techniques are largely based on the ore elements and associated trace elements (Cu, Pb, Zn, Ag, Au, Ba, Sn, W, Mo, Ni, Co, As, Sb, and Bi). Major elements are not used — either because of lack of analytical reliability or because it is believed that they do not enlarge the target. Most studies are empirical, with a preference for adapting or refining old methods rather than developing new and more appropriate techniques.

It is of interest to record a quite different situation in the People's Republic of China. Based on a one month visit as a guest of the China National Nonferrous Metals Industry Corporation, the writer had the impression of innovative work comparable with that in English-speaking countries. The Chinese also have the happy habit of giving more information on their mineralization and publishing maps with scales.

CONCLUDING DISCUSSION

Rock geochemical signatures of variable diagnostic specificity have been documented on various scales for many types of mineral deposits. The degree of certainty and the extent of general application depends to a significant extent upon the type of deposit and the degree of understanding of the genesis of the deposit. There are, however, a number of broad, general conclusions.

Regional-scale deposits of plutonic association Cu(Mo) porphyry deposits occur in I-type granitoids of intermediate composition, but there is no obvious geochemical distinction (except, possibly, Cu enrichment) within the large group that can be used to identify any particular granitoid as being potentially mineralized. Although Sn-(W)-U and rare metal deposits occur in S-type granitoids that are generally acidic, specialized, and highly evolved, specialization does not necessarily ensure economic mineralization. However, the greater the degree of specialization — indicated by Rb:Sr and K:Rb ratios — the greater the probability of mineralization. The trace element content of mineral separates and the contents of halogens may be useful to distinguish mineralized plutons within a region, but they show no consistency of behaviour between regions. Limited data on rare earths suggest the possibility that deviations from normal petrological trends may indicate mineralizing and alteration processes.

Local-scale deposits of plutonic association Porphyry deposits normally have haloes in excess of 1 km in diameter showing enhanced Cu, S, K, and Rb and depleted Ca and Sr. Haloes are characteristically zoned — with Cu(Mo) at the centre, succeeded

outwards by a variety of other metals (K, Rb, precious metals, As, Sn, W, Bi). Base metal anomalies usually form the outermost halo. Local-scale anomalies for Sn deposits include Sn, Rb, Sr, F, and Li.

Regional-scale massive sulphides of volcanic association The relation between Zn-Cu and Zn-Pb-Cu massive sulphides and the tholeiitic calc-alkalic classification of volcanic rocks is uncertain — it is now recognized that classification by traditional AFM diagrams is unreliable in altered rocks. There are insufficient data to determine whether classification of volcanic rocks through the use of relatively immobile elements (Y, Zr, Ti, Cr) will yield a genetic relation between lava and mineralization. Available data for rare earths are equivocal in determining genetic relations between mineralization and host rocks. Regional-scale anomalies have been documented in a few areas by simple ore metal or ore metal and element ratios and/or multi-element statistical relations. Ore metals and Mn in exhalites have also been shown to give extensive regional anomalies in some cases.

Local-scale massive sulphides of volcanic association There is a remarkable degree of consistency of local-scale geochemical response in time and space around massive sulphides. Haloes of up to several kilometres laterally and hundreds of metres vertically are defined by some or all of the following: enrichment of Pb, Zn, Fe, Mn, and Mg; depletion of Na and Ca. A variety of other elements — including Cu, Ni, Co, K, Rb, Sr, P, and precious metals — have a variable response in specific situations.

Vein and Replacement Type Deposits Deposits of this type in large mineral districts give rise to large, regional-scale anomalies. The most extensive haloes may be expected in samples of the "plumbing" system, such as vein- and fracture-fillings. The elements that respond include the ore elements and As, Sb, Bi, Hg, and Te. Intense wall-rock anomalies for the same general group of elements are normally restricted to a few tens of metres and show a characteristic logarithmic decay pattern.

Gold Deposits Gold deposits — from Archean to Tertiary — appear to have associated geochemical haloes for some of Au, As, Sb, Hg, B, Tl, Bi, Se, Te, Ag, and base metals. Pervasive alteration is normally indicated by enhanced levels of SiO₂ and K, and depletion of Na and, in some cases, Ca. Carbonatization is common around Archean deposits.

The widely increased availability of sensitive, multi-element analytical techniques has been a significant factor in an increasing use of geochemical data in economic geology investigations. However, in the earlier review of rock geochemistry (Govett and Nichol 1979) the diversity of elements that gave responses was stated to be an adverse factor affecting the applicability of rock geochemistry to exploration. The increasing availability of multi-element analyti-

cal techniques has expanded the list of elements that respond in any particular case even further. Nevertheless, it is now the writer's opinion that work over the last decade has demonstrated that, whereas many elements may respond in particular cases, practical geochemical responses for all types of metallic deposits can be obtained from a selection of about two dozen elements (Table 25.5). For particular types of targets, responses may be expected from some or all of less than 12 elements.

An inherent problem with the use of rock geochemistry is the theoretical difficulty of discriminating a geochemical signature due to a mineralizing event from geochemical variations due to other causes (e.g. fractionation, metamorphism, weathering). No difficulties due to metamorphic events are apparent in the literature, and limited data on even extensively weathered areas (Rugless and Govett 1984; Fedikow and Govett 1985) indicate that characteristic geochemical patterns are preserved. The geochemical effects of magma fractionation are a particular problem, especially with subtle anomalies. The most fruitful approach appears to be through a data normalization procedure using relatively immobile elements such as Ti and Zr.

Geochemical response around any particular target also varies as a function of rock texture. Thus, different scale responses are obtained between matrix and fragments in pyroclastics, between pyroclastics and lava, and between massive and spheroidal lavas. Similarly, different responses will be obtained from a host rock compared to fracture-fillings in the host rock.

There has been considerable interest in REE geochemistry but the general applicability of results — or advantages over the use of more readily determined conventional elements — has yet to be demonstrated. On both a regional and local scale, data on stable isotopes of hydrogen and oxygen, and on fluid inclusions offer the potential of locating the focus of the heat source and direction of solutions movement in hydrothermal systems. The work of Smee and Bailes (1986) using the distribution of conventional elements to determine the direction of brine movement and heat sources at a massive sulphide deposit is an indication of the degree of sophistication that has been achieved in the interpretation of rock geochemical data.

Even ten years ago gold was considered one of the more difficult metals to seek using exploration geochemistry. This has changed dramatically through the exploration-led "explosion" in both geological and geochemical studies on Au deposits. It is probable that before the next decennial symposium on exploration, gold exploration will be the best understood and most successful application of rock geochemistry.

Insofar as bedrock as a sample medium has not had the homogenizing and averaging processes enjoyed by soils and stream sediments, collection of representative samples at an appropriate density and of an appropriate physical size assumes critical importance. Both the required sample density and size are determined by the nature of the target, the chemical and physical character of the rock, and the concentration and mode of occurrence of the elements of interest. Equally important considerations are the nature of sample preparation, sub-sampling for analysis, and the analytical technique employed. The increasing interest in using elements that have abundances in the ppb range (e.g. Au, Te) demands adequate care to ensure that the sampling and analytical techniques are suitable to detect background concentrations.

In the last decennial review of rock geochemistry it was stated that the technique was being used sparingly by the mining industry. This situation has changed, and rock-chip geochemistry now appears to be widely used in mineral exploration as a routine procedure, although all of the case histories reported here have been "after the event" studies. Company geologists have, however, informed the writer of many unpublished exploration programs where rock geochemistry has had a significant role in the discovery of mineral deposits.

The use of the techniques in surface rocks is, of course, constrained by the availability of outcrop. There is no such constraint on using rock geochemical methods on drill core. However, to date there has been only limited use in this context (probably because of the impractical time lag between sampling and the availability of analytical data).

The successful commercial application of rock geochemistry has been perceived as requiring a multi-element approach with the attendant difficulties requiring complex multivariate statistical interpretation. To some extent, this is the case, but the perception has been exaggerated. The writer believes that evidence presented in this review demonstrates that responses for all types of deposits can be obtained from relatively few elements. Moreover, although statistical multivariate analysis undoubtedly assists in interpretation or extends recognizable anomalies in some cases, a combination of single element responses, or simple element ratios, is adequate in many situations. It is believed that recognition of this will lead to a considerable increase in the use of rock geochemistry in mineral exploration during the next decade.

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TABLE 25.5. SUMMARY OF ELEMENTS THAT MOST CONSISTENTLY GIVE SIGNIFICANT GEOCHEMICAL HALOES FOR VARIOUS TYPES OF DEPOSITS.

ELEMENTS	GRANITOIDS				VOLCANIC		VEIN		GOLD	
	Regional		Local		Regional	Local	Regional/Local		Regional	Epithermal
	porphyry	Sn-U-W	porphyry	Sn-U-W						
Na			(X)	(X)	X	X			X	X
K		X	X	(X)	(X)	X			X	X
Ca			X	(X)	X	X			(X)	(X)
Mg		X	(X)	(X)	X	X			(X)	(X)
Fe					X	X			(X)	(X)
Mn			X		X	X				
Rb		X	X	X		(X)				
Sr		X	X	X		(X)				
Li		X	X	X						
Ba		X			(X)	(X)				
As										
Si									X	X
Bi									X	X
Te									X	X
Hg									X	X
ore elements	Cu?		Cu, Zn, Mo, S	Sn, U, W	Zn	Cu, Pb, Zn, S	Cu, Au, Ag etc		Au, (S)	Au, (S)
others				F					CO ₂ , SiO ₂ , W	SiO ₂ , W

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EXPLORATION '87 PROCEEDINGS

GEOCHEMICAL METHODS: THEIR APPLICATION TO ORE EXPLORATION

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26. Exploration Geochemistry in Areas of Deeply Weathered Terrain: Weathered Bedrock Geochemistry

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ABSTRACT

In deeply weathered terrain, primary geochemical-dispersion patterns associated with mineralization are commonly modified as a result of selective mobilization and redistribution of elements. Such modification can include leaching, enrichment, lateral dispersion, and vertical differentiation, depending on the mobility of individual elements under the physical and chemical conditions prevailing during each of possibly several weathering episodes. In such areas, surface geochemical-sampling media, such as soils, lags, and stream sediments, largely reflect the chemical characteristics derived from deeply weathered rock which may differ appreciably from the primary dispersion patterns below the weathered zone. Innovative sampling and analytical approaches may be required to ensure the detection of dispersion patterns related to bedrock mineralization by low-cost surface techniques.

Concealment of prospective terrain by deep, transported overburden is a relatively common problem in complex terrains, such as the Yilgarn Block in Western Australia, where the products of multiple deep-weathering cycles dating from the Mesozoic are retained and overprinted by the signature of the currently prevailing arid climate. In such circumstances, weathered bedrock is frequently the preferred sampling medium for geochemical exploration. The high cost of sampling, when drilling may be required to reach depths of between 5 and 100 m, dictates that weathered bedrock geochemistry is most appropriately used in follow-up programs to test zones of interest defined initially by other techniques.

INTRODUCTION

Deep rock weathering is a feature of areas with a humid tropical climate, or those subjected to such climatic conditions in the geological past. Such areas include large parts of Australia, Asia, Africa, and South America. Although some important ore deposits occur within weathered rock, for most practical exploration purposes, the zone of deeply weathered rock must be regarded as a barrier or screen interposed between what can be observed and measured at the surface and the primary target of exploration — an ore deposit in fresh rock. At some stage in any geochemical program in such areas, it is usually necessary to sample, analyze, and interpret the

significance of the results obtained from weathered bedrock. It is therefore of great importance to understand the modifications to primary dispersion patterns that occur in the weathered bedrock zone, and how they relate to the more conventional surface media of soil, lag (Carver *et al.* 1987), and stream sediments.

This paper will review the dispersion patterns in weathered bedrock, which are characteristic of important ore deposit types, and discuss the role of weathered bedrock geochemistry within the panoply of geochemical search technology.

NATURE AND DISTRIBUTION OF DEEP ROCK WEATHERING

The nature of deep rock weathering is a complex subject and will be dealt with in greater detail elsewhere in this volume (Butt 1988 *see* Paper 28, this volume). The processes are generally thought to be operative in humid tropical climates, with alternating wet and dry seasons. Interaction with both oxygenated meteoric water and groundwater, augmented by humic substances, results in the decomposition of the principal rock-forming silicates, mobilizing such major elements as Na, K, Ca, Mg, Fe, Al, and Si. Most of these elements are leached from the unsaturated zone and, to a considerable degree, from the zone of intermittent saturation. Some components such as Fe, Mn, and Al may be redeposited and concentrated about the water table by both descending and ascending waters, giving rise to the sesquioxide-rich "B" horizon, which is one of the main characteristics of lateritic-weathering profiles. The residue, above and below the zone of sesquioxide enrichment, consists in varying proportions of quartz and clay minerals, together with resistant primary minerals such as the spinel group, zircon, sphene, and tourmaline. Seasonal and longer-term vertical movements in the water table add complexity in the form of secondary zones of Fe concentration, including the aptly termed "mottled" zone. Silica released during the breakdown of mafic minerals such as olivine and pyroxene is frequently redeposited in irregular vuggy masses within the clay zone, deeper in the profile.

Together with the redistribution of the major elements during deep weathering are profound changes in the distribution of many of the trace elements of importance in geochemical exploration. In particular, elements whose behaviour in the secondary environment is influenced by iron are likely to

be subject to redistribution, often in patterns with a pronounced horizontal component, paralleling the water table and the land surface. Notable amongst these elements are copper and gold as will be seen in the following sections.

The typical deep weathering profiles of the Western Plateau of Australia are believed to have formed over a range of overlapping periods from early Mesozoic to mid-Cenozoic (Butt and Smith 1980). During the onset of aridity the lowering of the water table probably increased the depth of weathering. Rejuvenation of drainage following tectonic uplift has resulted in partial dissection of the deep weathering profile, the products being redistributed more or less locally to add to the problems of concealment of the underlying geology. Retention of an iron-rich crust at the top of the weathered bedrock profile is an important feature in arid areas where the sesquioxide horizon had been eroded (Figure 26.1).

GEOCHEMICAL DISPERSION PATTERNS IN WEATHERED BEDROCK

An abundance of data is potentially available from drilling programs and sampling carried out during opencut mining to contribute to an understanding of the distribution patterns for elements of economic interest in weathered bedrock. Unfortunately, very few such studies have been published.

NICKEL-COPPER MINERALIZATION

Nickel is one of the most mobile elements during lateritic weathering, as is indicated by the numerous and widespread occurrences of ore-grade Ni deposits developed in the clay zones of lateritic profiles

over unmineralized rocks. In fact one of the major problems of Ni exploration in deeply weathered terrains is to distinguish concentrations of lateritic origin from those related to underlying sulphides. Copper, which generally accompanies Ni in sulphide deposits, even though at concentration levels from one to ten percent of those of Ni, is often a better guide to Ni sulphide deposits than Ni, despite the tendency for Cu to be similarly enriched in lateritic profiles (Smith 1977). There is a tendency for Cu maxima to coincide with Fe peaks in the upper part of the profile whereas the main concentrations for Ni occur deeper in the clay zone. This is illustrated by the contoured cross sections for a small Ni sulphide occurrence located below a complete laterite profile, near Kalgoorlie (Figure 26.2). Nickel shows severe depletion in the upper horizons of the laterite profile, with only moderate values in saprolite, whereas the anomalous Cu associated with the ore can be traced to within a metre or two of the surface. However, the limited lateral extent of even the copper anomaly in this example indicates the need for very closed-spaced drilling (<20 m) to detect this sub-economic occurrence. Somewhat broader patterns for Ni are associated with the more economically significant Redross Deposit, southwest of Kambalda, where the lateritic profile has been partially eroded (Knowles 1976). Although leaching of Ni is evident in the uppermost 3 m of the weathered bedrock, there is a suggestion of lateral dispersion between depths of 5 and 15 m to widths twice that of the host ultramafic.

BASE-METAL SULPHIDES

By comparison with Canada, there have been relatively few discoveries made of volcanogenic massive sulphides in the Australian Archean. Many geos-

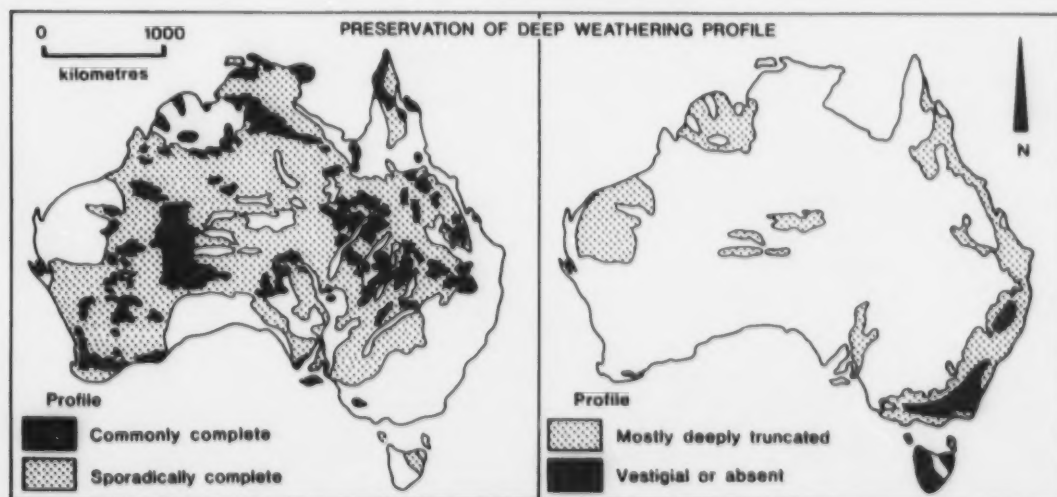


Figure 26.1. Distribution of deep-weathering profiles in Australia (from Butt and Smith 1980).

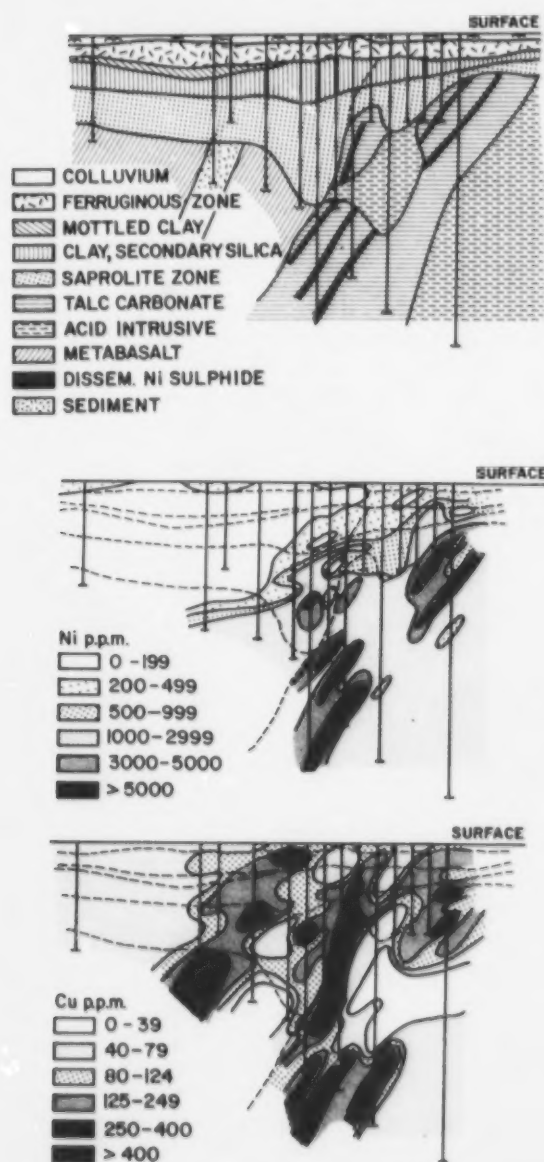


Figure 26.2. Nickel and copper dispersion patterns associated with nickel sulphide mineralization in a lateritic-weathering profile, near Kalgoorlie, Western Australia (from Smith 1977).

cientists attribute this to deep rock weathering and the problems associated with it in both geophysical and geochemical exploration. Certainly the severity of weathering is particularly marked over felsic volcanic sequences, and those occurrences of base-metal sulphides that have been discovered tend to be characterized by extreme base-metal leaching. This is confirmed by data from the Teutonic Bore Deposit, which shows depletion of Cu and Zn to background levels in the upper 10 to 15 m of

weathered bedrock (Figures 26.3 and 26.4). A broad anomaly is shown by Pb (Figure 26.5) with values of up to 3000 ppm within a 200 m wide halo of >250 ppm Pb immediately below the surface. Arsenic also shows a well developed anomaly extending to the surface (Figure 26.6). It is significant to note that all four elements exhibit strongly developed lateral-dispersion patterns with loci of maximum enrichment at depths of 20 m for Pb and As, 30 m for Cu, and 65 m for Zn. These patterns are approximately ten times more extensive laterally than the actual orebody and thus enlarge the exploration target to a significant degree.

In Namibia, Scott (1975) demonstrated the existence of broad, weathered bedrock anomalies associated with the Otjihase Prospect (Figure 26.7), but in this case the zone of maximum lateral dispersion occurs at the surface, even though the oxidized zone of the ore structure is depleted in Copper to a depth of approximately 30 m. Similar broad anomalies were found to be developed in surface outcrops of oxidized rocks adjacent to base-metal mineralization at Mykonos, Greece (Lahti and Govett 1981). It is not clear whether these differences in the disposition of the zone of maximum lateral dispersion reflect variations in the weathering regime or changes in the postweathering conditions.

GOLD MINERALIZATION

The recent surge in exploration activity for gold mineralization, coupled with the ability of modern analytical techniques to measure background abundance levels for gold, have added considerably to knowledge of gold dispersion. Mann (1984) postulated mobilization of gold in lateritic profiles with reprecipitation and concentration at the base of the Fe- and Al-rich sesquioxide horizon. Gold dissolution is aided by the extraordinarily low pH levels which have been documented in weathering profiles and is thought to accompany redox reactions of ferrous to ferric Fe. The relationship to the groundwater table and the land surface would be expected to produce a strong horizontal component in the resulting dispersion patterns for gold. Patterns of precisely this type were found to occur at the recently discovered lateritic Au deposit at Boddington in the southwest of Western Australia (Davy and El-Ansary 1986). At Boddington, there are in fact three superimposed horizons of gold concentration, each characteristically Fe-rich, possibly related to variations in the level of the water table at different times. The Boddington data suggest lateral dispersion of gold in weathered bedrock up to 500 m from the source mineralization in basement rocks.

A similar dispersion pattern has been documented over the Dingo Hill Deposit at Badgubup, situated about 300 km southeast of Perth, where the laterite profile remains intact (Figure 26.8). At the nearby Jinka's Hill Deposit, where the laterite profile has been eroded, there is no horizontal pattern



Figure 26.3. Copper dispersion in weathered bedrock from the Teutonic Bore massive sulphide deposit, Western Australia (from Greig 1983).

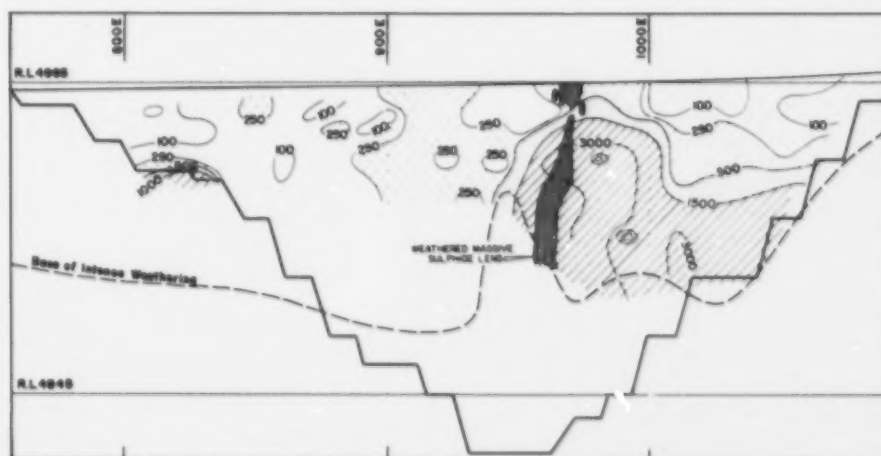


Figure 26.4. Zinc dispersion in weathered bedrock from the Teutonic Bore massive sulphide deposit, Western Australia (from Greig 1983).

of secondary dispersion, and in fact there is a suggestion of surface leaching (Figure 26.9). It should be noted that soil response in this case related more closely to the structural outcrop of the ore zone, whereas at Dingo Hill the peak of the anomaly in soil and laterite pisolites was displaced towards the hanging wall, and presumably relates to the laterite developed over the highest grade ore in the supergene zone.

Truncation of the laterite profile is common in the more arid Goldfields areas of Western Australia, but the horizontal or "mushroom"-type dispersion pattern seen in lateritic areas remains a characteristic feature. This may be the result of the horizontal zone of Au enrichment "riding down" with the land

surface, or may be due to upward movement of Au in saline soil moisture in response to evaporative gradients. In either case, the Fe-rich nature of the uppermost part of the weathered bedrock no doubt plays an important role in fixing and concentrating the Au. Figure 26.10 shows this type of pattern associated with a small gold occurrence to the northwest of Kalgoorlie (Carver *et al.* 1987). It is not clear whether the upper and lower portions of the dispersion pattern are linked, since the ore structures are characteristically narrow and steeply dipping, and are thus difficult to intersect with vertical drill holes. Figure 26.11 is an attempt to generalize the dispersion pattern associated with a typical, steeply dipping, lode gold deposit in the eastern Yilgarn Block of Western Australia. Characteristic features are the

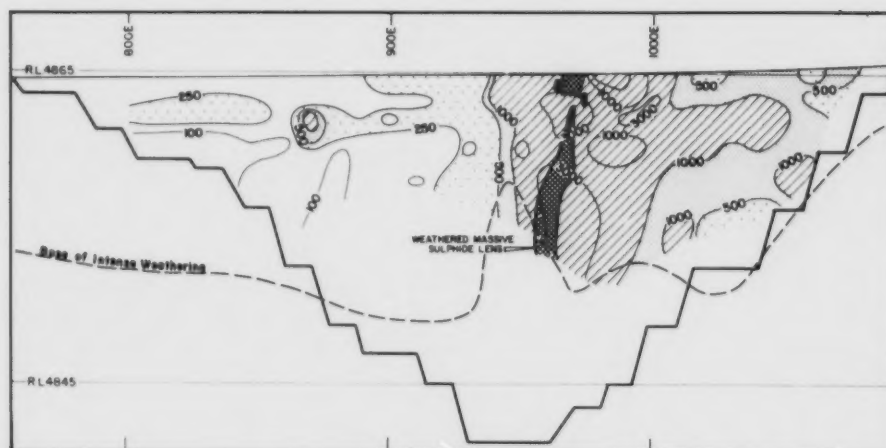


Figure 26.5. Lead dispersion in weathered bedrock from the Teutonic Bore massive sulphide deposit, Western Australia (from Greig 1983).

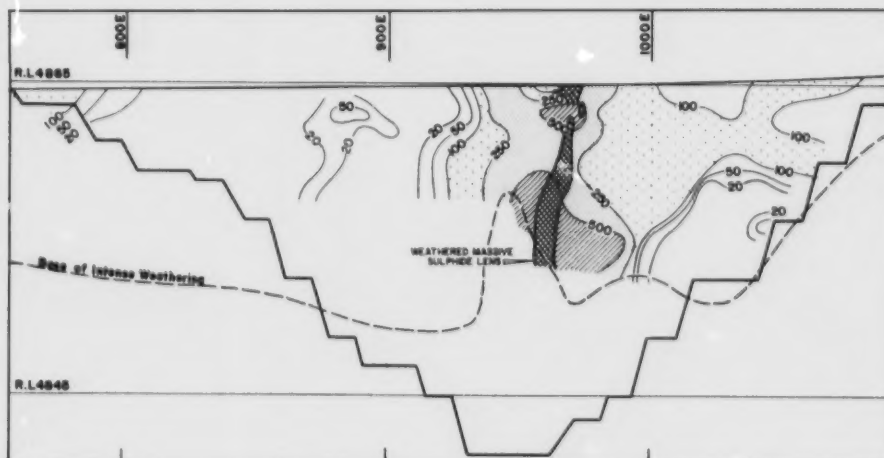


Figure 26.6. Arsenic dispersion in weathered bedrock from the Teutonic Bore massive sulphide deposit, Western Australia (from Greig 1983).

broad mushroom-shaped anomaly at the surface, and the zones of leaching and supergene enrichment. The top of the mushroom presents a large target for exploration but the narrowness of the stem, the small target represented by the zone of supergene enrichment and the low values in the leached zone have often led to the premature abandonment of worthwhile prospects. A comparison of the dispersion patterns described above from what is now a semiarid to arid environment with an example forming in lateritic soils under a prevailing humid tropical climate in the Ivory Coast (Figure 26.12) reveals clear similarities. There seems little doubt that the basic features of the Western Australian patterns were inherited during a more humid climatic episode than the one presently prevailing.

WEATHERED BEDROCK SURVEYS

CONTEXT OF WEATHERED BEDROCK SURVEYS

Geochemical surveys using weathered bedrock as the sample medium are usually employed in the follow-up of anomalies delineated by other means, such as soil sampling or geophysical techniques. In most circumstances, soil or lag sampling is preferred as the initial geochemical technique because of the enlargement of the target brought about by secondary-dispersion processes. However, selective sampling, designed to delineate zoning patterns about ore bodies, can lead to very large targets in bedrock, as is demonstrated by the work which led to the discovery of the Cortez gold deposit in Nevada (Erick-

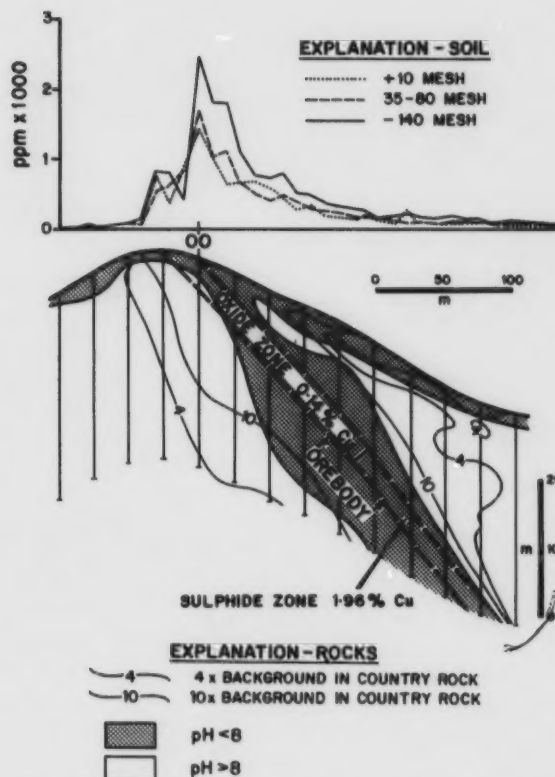


Figure 26.7. Copper distribution in soil and rock, Otjiase Deposit, Namibia (from Scott 1975).

son *et al.* 1966). Targets may also be sufficiently enlarged as a result of weathering processes, as described above, to make systematic sampling of bedrock feasible in a regional geochemical survey (e.g. Lahti and Govett 1981). Other circumstances which make weathered bedrock attractive as the sampling medium in first-pass exploration arise when surface materials are either not available or are unsuitable as sampling media. The nonavailability of soils can arise in situations of extreme relief or climate, such as extremely cold, arid, or mountainous terrain, or combinations of these. The most common circumstance in which surface soils or lags are unsuitable as sampling media arise in areas of transported overburden, where dispersion patterns developed in surface materials bear no spatial relationship to mineralization at depth. An example would be the bedrock geochemical survey carried out to delineate nickel sulphide ore at Windarra in Western Australia where the prospective zone is extensively concealed by transported overburden (Smith *et al.* 1980). Another circumstance in which sampling of bedrock is attractive is where surface soils are contaminated by past mining or industrial activity. Examples in this case include surveys made at Cripple Creek, Colo-

rado (Gott *et al.* 1969) and at Coeur d'Alene, Idaho (Gott and Botbol 1973).

LOGISTICS OF WEATHERED BEDROCK SURVEYS

In areas of abundant outcrop, bedrock sampling may be simply and inexpensively carried out by collecting composite or single rock-chip samples at the surface. Work of this type has been responsible for discoveries such as the Corktree Well gold deposits, which occurs in a banded iron formation outcrop in the otherwise poorly exposed terrain to the north of Laverton, in Western Australia (Reid 1979). The effectiveness of this approach in anomaly follow-up is dependent on the continuity of outcrop. If there is a risk of failing to detect significant mineralization because it may occur in a gap in the outcrop, and thus may not be sampled, it is necessary to resort to slower, more expensive methods of sampling such as pitting, trenching, or drilling.

Trenching is often particularly valuable in anomaly follow-up because the continuous exposure permits both structural observations and sampling intervals which can be matched to observed geological boundaries. It is, however, expensive and not always effective in areas of intense weathering or deep soil cover.

Drilling for weathered bedrock geochemical samples has become a widely practiced geochemical technique in Western Australia, in both reconnaissance and detailed follow-up. Where relatively shallow holes suffice (<40 m) light rigs can be used at a cost of A\$5 to A\$10 per metre. These include simple auger types, vacuum (in which the sample is drawn up the rod-string under vacuum), and rotary-air-blast (RAB) in which the sample is forced by compressed air between the rod-string and the hole wall. For deeper sampling in holes to 100 m or so in depth, reverse circulation (RC) sampling equipment may be required to be used in conjunction with a down-hole hammer-percussion rig. In this system, the cuttings are entrained in a stream of compressed air which passes down a sleeve in the rod-string. This results in reliable sampling of weathered materials, even below the water table, but often at a cost of A\$25 to A\$30 per metre.

Application of this type of exploration in concealed areas provides geological as well as geochemical data. The ability to identify primary lithologies from chips of weathered bedrock is an acquired skill necessary for exploration in weathered terrain. Here again, geochemical techniques using relatively immobile elements such as Cr, Ti, and Zr to identify igneous rock types can play a part (Hallberg 1984).

Other considerations in planning bedrock geochemical surveys can best be illustrated by reference to some actual examples. Butt and Sheppy (1975) report on the search for Ni sulphides in the Mount Keith area, where the host ultramafics are concealed by up to 25 m of transported alluvium. Drilling was

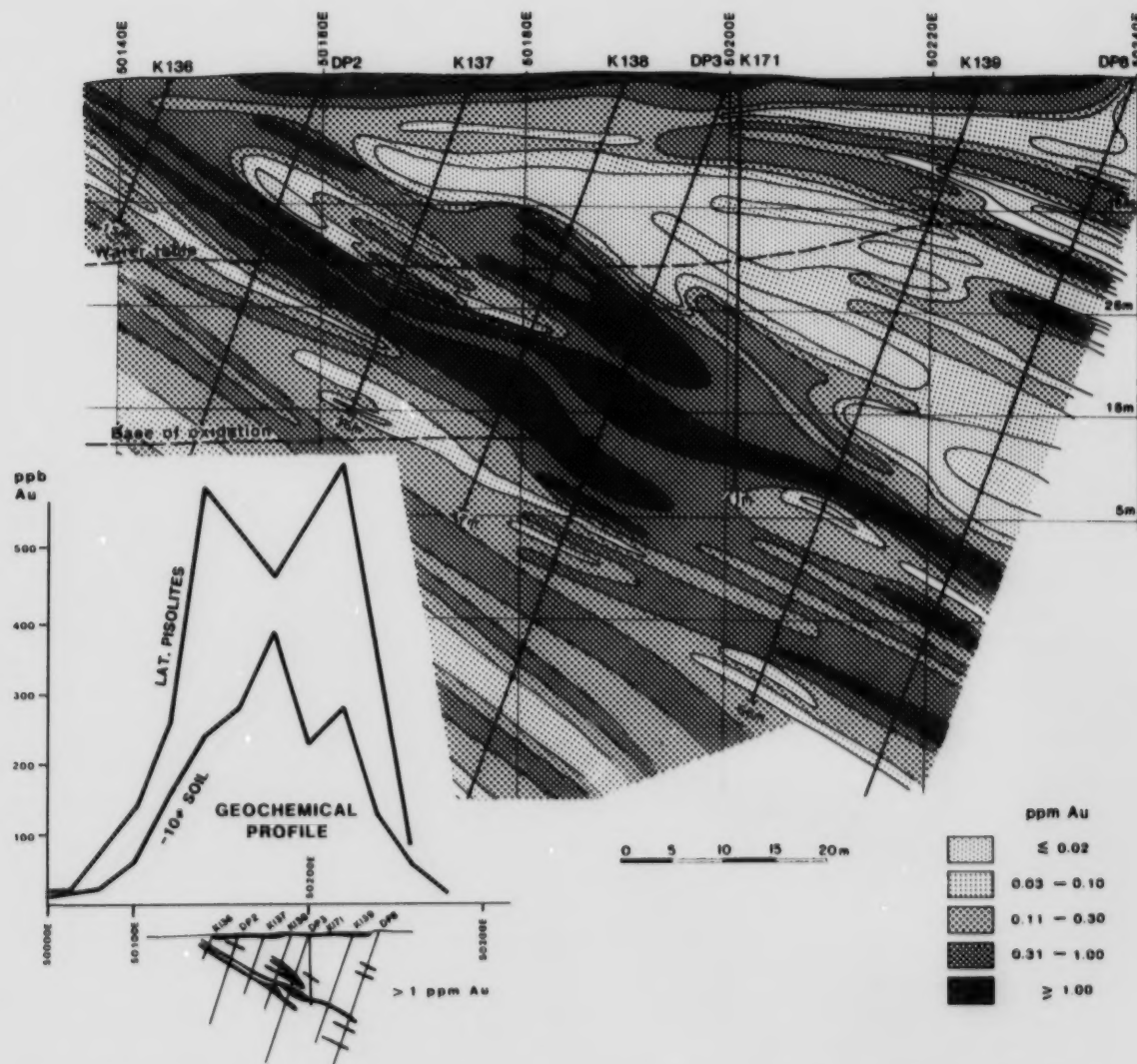


Figure 26.8. Gold dispersion in weathered bedrock, soil, and lateritic pisolites, Dingo Hill, Badgebup, Western Australia.

carried out over the ultramafic stratigraphy as outlined by magnetic surveys, initially at a 305 by 100 m spacing, closing down to 150 by 15 m in areas of interest. The diversity of materials encountered at constant depth created difficulty in the selection of suitable samples and the practice adopted was to select the highest analysis over a broad spectrum of depths. It was found that drillholes within the orebody which analyzed 1200 to 3000 ppm Ni at 30 m depth, corresponded to grades of 1.5 to 2.5 percent Ni in fresh rock at greater depth. Holes in which Ni exceeded 4000 ppm and in which copper exceeded 300 ppm were regarded as anomalous. However, these criteria were only partly successful when applied to the results of routine RAB drilling, many anomalies subsequently tested being ascribed

to low-grade sulphides or lateritic enrichments related to barren ultramafics. An added problem was the frequency of aborted holes because of the prevalence of cavernous and hard siliceous zones. A similar program was used to explore the Windarra ultramafic over a strike of some 25 km (Smith *et al.* 1980). Apart from the inconspicuous gossan outcrops which led to the initial discovery of Ni sulphides at Mount Windarra, concealment by up to 30 m of alluvial and aeolian overburden is widespread. Where overburden was relatively shallow, sampling was by means of an auger drill on patterns of 120 by 6 m, closing to 15 by 1.5 m in anomalous areas. An RC-percussion rig was used on a 240 by 60 m initial grid in areas of deeper overburden. A sampling interval of 1 to 2 m was adopted, it being

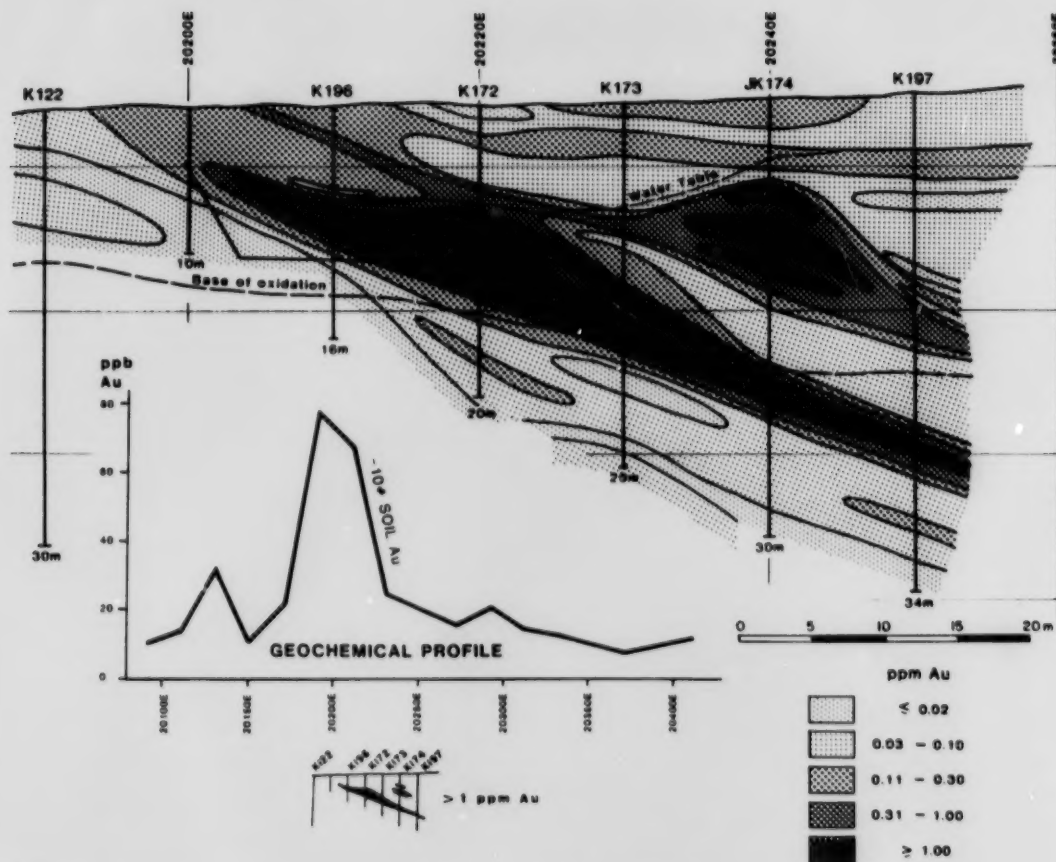


Figure 26.9. Gold dispersion in weathered bedrock and soil, Jinka's Hill, Badgeup, Western Australia.

left to the driller to select from the laid-out samples what was thought to be the top of weathered bedrock. Anomaly threshold values in weathered bedrock were 2500 ppm Ni and 256 ppm copper. This work located a second major deposit at South Windarra, and was regarded as a successful test for near-surface mineralization, at the same time contributing valuable geological information. This distribution of Ni and Cu in weathered bedrock is shown in relation to geology in the immediate environs of the Mount Windarra mineralization in Figure 26.13.

The use of bedrock geochemistry intensified during the period of base-metal exploration in Western Australia in the 1970s. The movement toward deep sampling received impetus from unofficial reports of the discovery of the high-grade Scuddles copper-zinc deposit in the Golden Grove District, 1 km to the north and along the same stratigraphic horizon as the significant Gossan Hill Orebody. Whereas Gossan Hill — as the name implies — was a conspicuous outcrop of gossan, from which base metals had been strongly leached, the new discovery was located in a topographic low with lateritic soil

cover. According to industry gossip, the Scuddles Deposit was so leached that it had been necessary to drill to depths of 80 m to obtain definitive geochemical samples. With the benefit of hindsight, it is important to note the work of Smith and Perdrix (1983) which showed that both deposits could have been located by the analysis of lateritic surface pisolites for appropriate pathfinder elements.

Bedrock geochemistry continues to find wide usage in the current spate of gold exploration in Western Australia, despite even greater evidence that cheaper surface-sampling techniques can be effective. The broad "mushroom"-type dispersion patterns developed in weathered bedrock over gold deposits certainly represent excellent targets for bedrock-drilling programs. However, the resulting anomalies are often very extensive and much additional drilling is required to locate and evaluate the anomaly source.

In one example of the misuse of bedrock geochemistry, RAB drilling had been programmed in a belt of hilly terrain with intermittent silicified outcrop. Because of the silicification, the drilling was

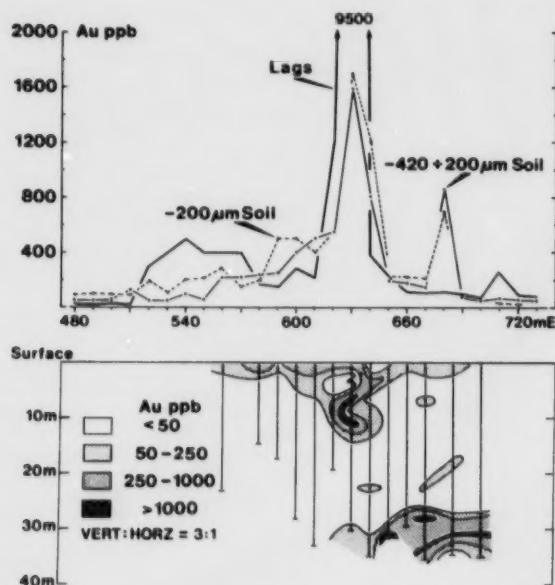


Figure 26.10. Gold dispersion in weathered bedrock, lag, and soil over gold mineralization in Eastern Goldfields, Western Australia (from Carver et al. 1987).

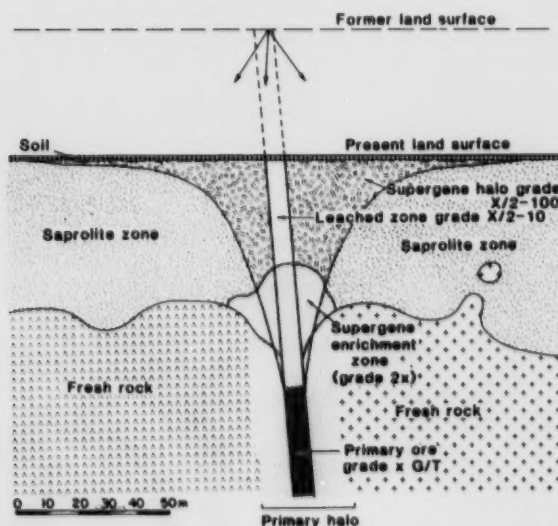


Figure 26.11. Generalized profile through a deeply weathered gold deposit.

slow and expensive and most holes had stopped in semifresh bedrock at depths of from 1 to 3 m. Distinctly anomalous results (0.01 to 0.5 ppm gold) were recorded in numerous holes on several traverses. However, none of the results were ore grade and the work did not provide the focus necessary to site follow-up RC-percussion holes. Surface lag

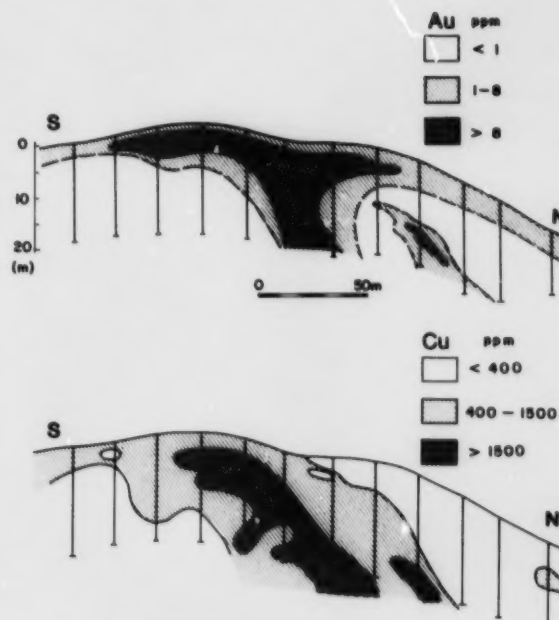


Figure 26.12. Gold and copper distribution in lateritic soil over a gold-copper vein, Ivory Coast (from Bradshaw and Thomson 1982).

sampling, on the other hand, conducted at the same sampling intervals as the RAB drilling defined strong and distinct anomalies, with significant contrast from one traverse to another. Follow-up lag sampling defined a series of discrete drilling targets which have still to be tested. It is concluded that the RAB drilling failed to differentiate between the minor mineralization, which was available on virtually every traverse, and the dispersion patterns associated with a major mineralized source.

DISCUSSION

There is a common tendency for explorationists in Western Australia to conduct drilling for bedrock geochemical samples in first-pass exploration because of suspicion — frequently unwarranted — as to the transported nature of the overburden. The greatly increased expense of such work is "justified" by the assumption that "at least it gives a reliable sample". This supposition is open to challenge on both theoretical and empirical grounds.

The search for a small object in space becomes exponentially more difficult as the degrees of freedom are increased. It is a simple enough matter to locate an object in one dimension. It is for this reason that most systematic exploration is carried out on traverses with the spacing of observations along the traverse designed to detect anomalies of dimensions likely to be significant. If the search area has two dimensions (i.e. planar) then many more observations are needed to locate a given target. Concep-

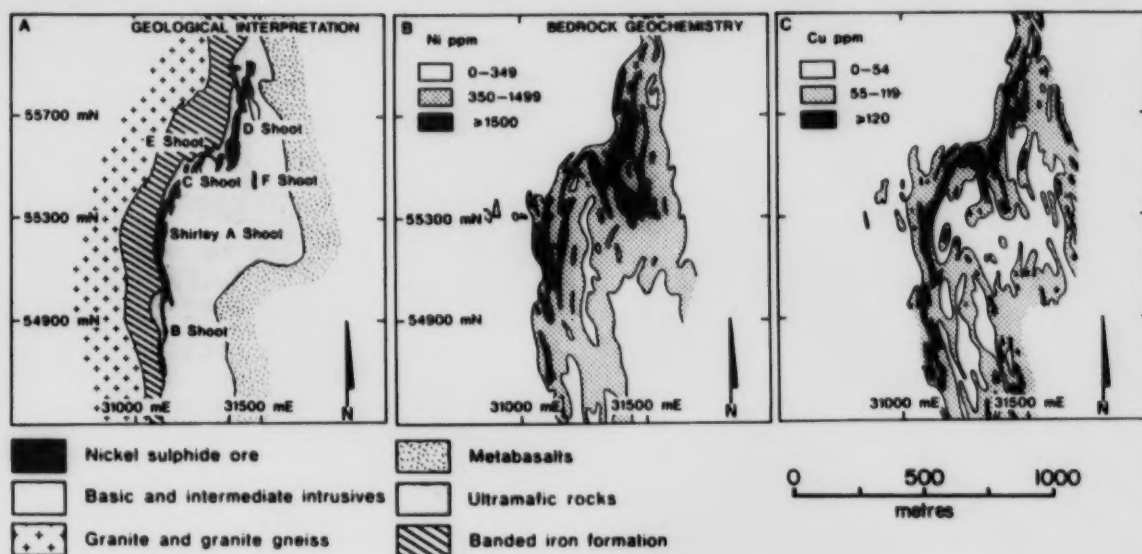


Figure 26.13. Interpreted geology and weathered bedrock geochemistry, Mt. Windarra: A) Geology, B) Nickel distribution, C) Copper distribution (from Smith et al. 1980).

tually, the land surface may be regarded as a plane which almost all ore structures will intersect somewhere. The trace of such intersections, usually enlarged by secondary dispersion processes, are targeted by arrays of traverses with orientation and spacing designed to locate significant occurrences. Once found, such intersections, or anomalies, provide invaluable reference points to guide more detailed follow-up exploration.

Drilling for bedrock geochemical samples introduces a third dimension to the search, which entails either many more observations (or samples analyzed) or the judicious selection of a particular depth or material to be sampled. Given the generally more restricted halos developed in the primary zone and the complexities introduced by geological structure and the weathering processes, the opportunity for sampling all around an orebody without detecting its presence is much greater with a drilling approach than with surface sampling.

In many of the examples cited in this paper, it has been apparent that inexpensive surface geochemical techniques could have delineated the target zone more efficiently than bedrock geochemistry (see Figures 26.7, 26.8, 26.9, and 26.10). Comparative data are not available for the Kalgoorlie Ni, Teutonic Bore, Mount Keith, and Windarra examples, but given the success of surface techniques over the strongly leached Golden Grove Deposits, together with the fact that the ore zone crops out as gossans in at least three of the above cases, it seems likely that exploration could have been carried out more cost-effectively by other methods. That bedrock geochemistry has its place in

exploration is not in dispute; however, it is contended that it has been overused in the Australian context to the point of abuse. This has had a detrimental effect in terms of the cost of discovery, impacting on the general cost-effectiveness of exploration expenditure and the role played by geochemical exploration in particular.

The cost comparison between surface sampling and drilling for geochemical samples is illustrated in Figure 26.14. Costs per square kilometre have been calculated for reconnaissance (400 by 50 m sampling grid), follow-up (200 by 20 m), and detailed (50 by 20 m) surveys. Two different types of drilling have been taken into consideration. If shallow drilling is effective, rotary-air-blast (RAB) drill holes to a depth of 30 m are effective, costing A\$10 per metre (that is a cost of A\$300 per sample site). Analytical costs have also been approached in two ways. The conservative approach necessitates analysis of the entire hole at 1 m intervals, which at an all-inclusive cost of A\$10 per sample, amounts to an additional A\$300 per sample site. Analytical costs can be reduced by either compositing samples over broad intervals or sampling selectively from depth horizons thought likely to reflect proximity to mineralization (e.g. ferruginous zones for maximum likelihood of gold or copper response). In this case, an average of three samples per hole is assumed. This approach involves some risk that a dispersion halo might be intersected by the hole but not recognized because the critical interval is not sampled. If there is a need to sample at greater depths, a rig capable of reverse circulation (RC) or percussion drilling might be required to recover reliable samples from

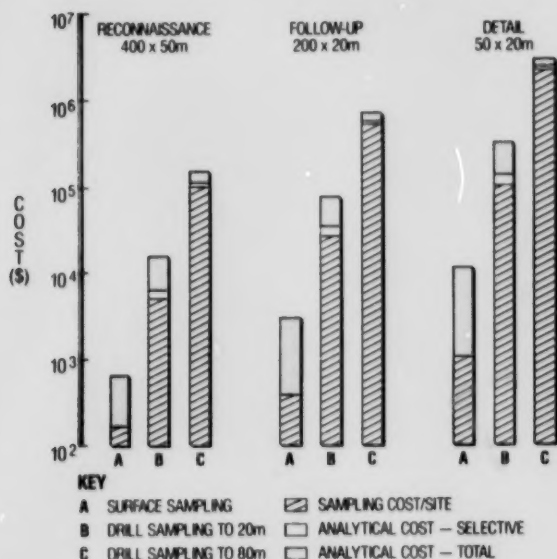


Figure 26.14. Cost comparison: Surface versus bedrock geochemistry (cost per square kilometre).

average hole depths of 80 m. At costs of A\$25 per metre, the sampling cost escalates to A\$2000 per site, with a corresponding exacerbation of analytical costs. It can easily be seen from these data that, on the basis of cost, wherever reasonable confidence can be placed on the effectiveness of surface sampling, it should be used in precedence to drilling for bedrock samples. In fact even in areas where there is known transported overburden, the allocation of less than five percent of the geochemical budget toward surface sampling will usually provide a quick scan of the total area to be explored, with the possibility that some indications of mineralization will be detected through windows in the transported cover. Visual inspection seems to lead invariably to an unduly pessimistic view as to the depth and transported nature of overburden. This has often led to deferment of exploration of areas which have subsequently proved amenable to the successful application of inexpensive surface techniques. Targets generated by surface sampling tend to focus early drilling into areas likely to contain mineralization. In this way, information can be gained on the environment before committing to an expensive blanket-drilling test of unknown terrain.

CONCLUSIONS

Deep weathering imposes major changes in the dispersion patterns associated with ore deposits. Nickel, zinc, and to a lesser extent copper may be leached to variable depths in the profile. Gold, lead, and arsenic are less affected and in some situations display broad patterns of enrichment in the near-surface environment.

The mechanisms governing the distribution of trace elements are insufficiently well known to make general statements. However, it seems clear that redox reactions associated with ferrous-ferric iron transformations are influential in determining the disposition of zones of gold and copper dispersion. Retention of near-surface enrichment zones for these elements may be favoured by aridification. For gold, remobilization as the chloride complex, upward movement under evaporative gradients, and fixation in iron-rich horizons at the top of the weathered bedrock are probably important.

Bedrock geochemistry is most usefully applied in follow-up surveys but also finds application in areas where soils are poorly developed, polluted, or transported in origin. There has been a tendency, particularly in Australia, to use bedrock geochemistry in environments where inexpensive surface techniques would have been just as effective, if not more so. There is a growing appreciation that the sampling of appropriate surface media such as lag, including lateritic pisolites, for pathfinder elements which are minimally affected by leaching can overcome the problems associated with geochemical exploration in deeply weathered environments.

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27. Using Lateritic Surfaces to Advantage in Mineral Exploration

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ABSTRACT

Methods of using lateritic materials to advantage in exploration have evolved to the extent that laterite geochemistry is being used successfully in reconnaissance and follow-up for a variety of ore types, including gold deposits.

The unique geochemical characteristics of certain iron-rich accumulation materials that lie on lateritic surfaces offer considerable advantages to the effectiveness and economics of exploration for concealed mineral deposits. The main advantages are that specific materials can provide samples which geochemically represent concealed bedrock and any included mineral deposits, and that weathering processes over a long period of time have resulted in suppression of local-scale variation.

Lateritic weathering surfaces are widely distributed in various stages of development or preservation around the globe, particularly in the seasonally humid tropical/subtropical belts. They also can be preserved in regions which previously have experienced lateritic weathering, particularly in the Cretaceous to Tertiary period. In the past, the blanketing effect of lateritic materials in such deeply weathered terrain has had deleterious effects on exploration by weakening geochemical signatures of ore deposits, making recognition of rock type and gossans difficult, and by concealing bedrock and mineralization beneath accumulations of weathering materials. Recent developments in exploration technology have changed this situation dramatically.

Some methods of exploration for concealed gold and polymetallic mineral deposits are reviewed, drawing from recent exploration experiences in Australia. The generalized procedures discussed, however, have widespread application.

INTRODUCTION

The use of laterite geochemistry for mineral exploration has developed rapidly since the late 1970s. The purpose of this paper is to provide a statement on current use of laterite geochemistry, provide a brief review of developments, and propose an outlook. The paper draws particularly from recent exploration experiences in Australia where many of the techniques are in widespread use.

Acceptance and growth of laterite geochemistry as an exploration tool has come about because of several factors. First was the realization that, properly carried out, the geochemistry of surface or near-surface laterite can indeed detect concealed mineral deposits. This was shown by Tooms *et al.* (1965) in Mo exploration, Mazzucchelli and James (1966) using As for Au exploration, and extended by Smith *et al.* (1979) and Smith and Perdrix (1983) with a multi-element approach for polymetallic base-metal sulphide deposits, Zeegers *et al.* (1981) for Cu-Mo exploration, and Smith *et al.* (in press) for a wide variety of concealed deposits including Au. Techniques were established through research and adopted by the exploration industry, in some cases with refinement (Legge *et al.*, in press), for both reconnaissance and follow-up (see, for example, R.E. Smith 1987a, 1987b).

Critically important in establishing operational procedures were developments of analytical methods that enabled reliable determinations of the chalcophile elements, in particular, at the ppm level in lateritic materials which are characterized by a high and variable Fe content. In Australia, X-ray fluorescence techniques developed by K. Norrish (CSIRO) and B. Chappell (ANU) particularly using extended counting times, were applied to exploration geochemistry in the mid 1970s by A.M. O'Connell and M. Hart at CSIRO, and gained wide acceptance. The application of Inductively Coupled Plasma (ICP) emission spectroscopy techniques to the analysis of geological materials has also provided the capability of simultaneous (and therefore relatively low-cost) analyses of major, minor, and some trace elements.

Driven by the 1980s gold boom, the graphite furnace Atomic Absorption Spectrophotometry (AAS) technique was widely adopted by analytical laboratories world-wide, providing analyses for Au to ppb levels. This enabled for the first time, economic measurement of Au levels in laterites appropriate to exploration geochemical programs, thus greatly facilitating the delineation of Au dispersion haloes in lateritic duricrust.

Commencing with the Boddington gold deposit (Davy and El-Ansary 1986), discovered in 1981, and the Mt. Gibson gold deposit, discovered in 1983, both of which lie in the Archaean Yilgarn Block in Australia, was the realization that lateritic Au deposits can be important resources. Laterite

geochemistry provides the logical exploration tool for deposits such as these, as well as for concealed bedrock resources of a variety of commodities in lateritic terrain.

The ready availability of computing power at progressively decreasing capital costs has made possible routine handling of large volumes of multi-element geochemical data, and facilitated data display and interpretation. This in turn has made possible the application of multivariate statistical techniques which, if used correctly, can be powerful tools for exploration.

Today, laterite geochemical techniques are widely used in mineral exploration programs both for reconnaissance and follow-up. In Australia, some important discoveries of new Au deposits, mentioned below, have resulted from the application of such multi-element laterite geochemistry. Use of laterite geochemistry in exploration continues to expand and coupled with this is an acceleration of research into laterite geochemistry.

LATERITIC WEATHERING AND MINERAL EXPLORATION

Terrains with a history of deep weathering, much of which is lateritic, are distributed widely around the globe, particularly between Latitudes 35°N and 35°S. The relevance of geomorphology, climatic history, and development of weathering profiles of such regions is discussed by Butt (*see* Paper 28, this volume). Lateritization was widespread in the Cretaceous to mid-Tertiary time span and some regions

characterized by lateritic profiles, such as western Minnesota (Parham 1970; R.E. Smith 1987b), lie outside the belt of present-day lateritic weathering. A wealth of literature has focused upon the development of lateritic profiles and their characteristics. Prominent contributions include McFarlane (1976), Davy (1979), Nahon (1986), Butt (1987) and Lecomte (*in press*).

Prior to the early 1980s, the blanketing effect of lateritic materials in such deeply weathered terrain has had deleterious effects on exploration by weakening geochemical signatures of ore deposits, making recognition of rock type and gossans difficult, and by concealing bedrock and mineralization beneath accumulations of weathering materials. Lateritic regions have thus tended to lag the systematic mineral exploration that has characterized much of the rest of the world.

This situation has changed. Much attention is now focused upon lateritic regions because of the recognized importance of lateritic, saprolitic and supergene Au deposits hosted in lateritic profiles and resulting from lateritization or post-lateritization processes. Such deposits have become economically attractive targets for exploration because of developments in extractive technology (carbon-in-pulp and heap leaching processes) and the development in skills, particularly in Western Australia, of selective open cut mining (Chadwick 1987). Together these developments allow the profitable mining of low-grade irregularly shaped deposits, as shown in Figure 27.1. Under favourable circumstances even relatively small deposits of some 200 000 t at grades as

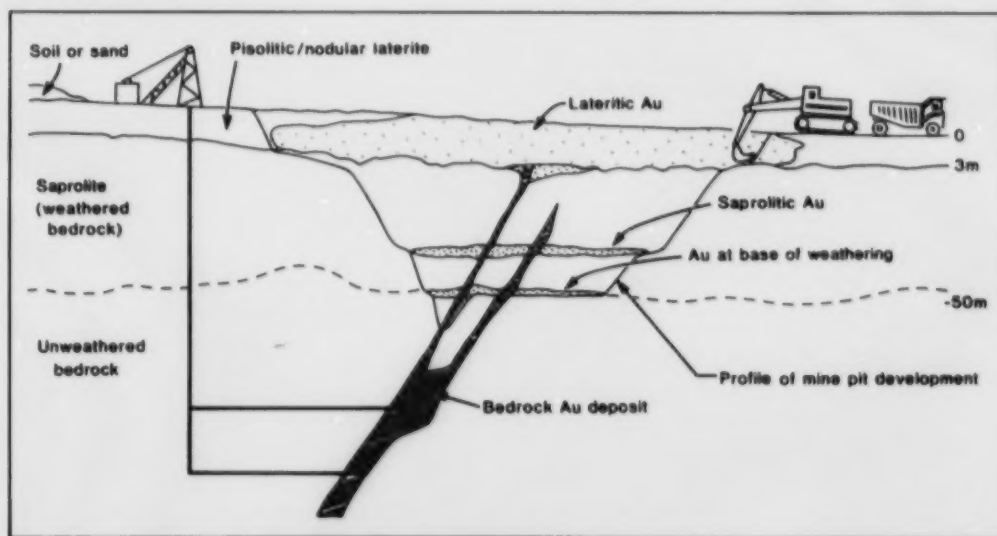


Figure 27.1. Profile through an idealized mid 1980s Au mining situation in lateritic terrain of the Archean Yilgarn Block, Western Australia, Australia. Grades as low as 0.5 g/t Au can be worked in the near surface lateritic material, and a cut-off of 0.5 g/t to 1.0 g/t Au is used in selective open-cut mining of saprolite. In order to provide a suitable source for Au in the laterite profile a bedrock source is required, although the grades are not always economic for hard rock mining.

low as 1 to 2 ppm Au are being worked, with material in the 0.5 to 1.0 ppm Au being stock piled for heap leaching.

Prior to the 1980s, many of these low-grade Au deposits would not have been viable and hence were not sought. Furthermore, some, because of the fine particle size of the Au, would probably be undetectable prior to the use of systematic Au geochemistry. As shown by West Australian examples, lateritic and supergene Au deposits can be both numerous and profitable. For these reasons lateritic regions of the world have become exploration frontiers.

SOME CHARACTERISTICS OF LATERITE PROFILES AND SURFACES

Lateritic landscapes owe their characteristics to weathering over long time-spans, typically some tens of millions of years. A characteristic of lateritic landscapes is the accumulation and subsequent hardening of Fe-oxyhydroxides, the Fe being made available by weathering of Fe-bearing minerals in bedrock deeper in the profile, to form a near-surface, Fe-bearing to Fe-rich duricrust. Several processes are involved in the formation of this residuum. Iron-oxyhydroxides are precipitated at the zone of oxidation that occurs near the top of the water-saturated part of the saprolite profile, involving the process of ferrollysis (Mann 1984). Iron oxyhydroxides can also accumulate as pseudomorphs after original Fe-bearing minerals. Nahon (1986) described some of these

processes. Important in formation of lateritic duricrust is volume collapse of saprolite under the influence of gravity. Saprolite is first made susceptible to collapse by being rendered porous and permeable due to dissolution of labile minerals and removal of components such as Na, K, Ca, and Mg in solution, and replacement of unstable minerals by less cohesive minerals such as kaolinite and gibbsite. Physical removal of fine clays and finely dispersed Fe-oxyhydroxides is important at the top of the saprolite profile, and fluvial processes (surface sheet wash, and subsurface groundwater flow) as well as aeolian processes are envisaged. These processes are facilitated by any physical disturbances of the profile by gullying, eluviation, growth of tree roots and their subsequent decay, and termite action.

The presence of such duricrusts, together with the subdued topographic relief often inherent in their formation, leads to a low degree of mechanical erosion of the duricrust itself, once it is sufficiently well-developed, particularly where stable vegetation retards surface erosion. Thus a lateritic residuum develops, commonly being 1 to 5 m thick, lying upon some tens of metres of kaolinitic saprolite, Figure 27.2.

Accumulation of residual quartz grains is very common and conspicuous both in the kaolinite- and gibbsite-cemented sandy matrix of some duricrusts, or within the Fe-oxyhydroxide nodules and pisolites, particularly where the bedrock types are

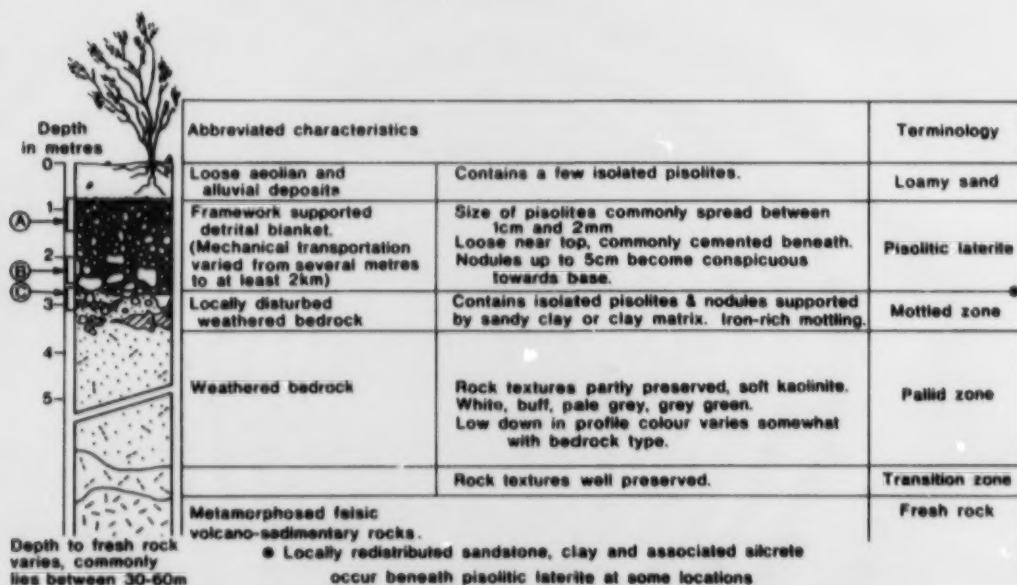


Figure 27.2. The Tertiary lateritic weathering profile from the Golden Grove District of the Yilgarn Block, Western Australia, from Smith and Perdrix (1983). In such terrain, reconnaissance geochemical sampling can be directed at the pisolitic laterite unit. Reproduced with the kind permission of Elsevier Science Publishers from the *Journal of Geochemical Exploration*.

granitic or felsic volcanics. Other resistant minerals released during weathering also accumulate, even though these may occur only in minor or trace amounts in bedrock. In this category are ilmenite, zircon, rutile, chromite, tourmaline, cassiterite, and scheelite. Accumulation of resistant accessory minerals broadly relates to the local parent rock type and thus contributes to geochemical background patterns. Of particular interest to exploration are anomalous abundances of residual minerals (for expediency usually established by geochemistry) that relate to concealed ore deposits. For example, anomalous abundances of finely dispersed cassiterite in lateritic duricrust can be one of the indicators for concealed base metal sulphide deposits, as at Golden Grove (Smith and Perdrix 1983).

The Fe-oxyhydroxides have an affinity for certain elements dispersing hydromorphically either through co-precipitation or by surface bonding (Nickel and Daniels 1985). Included in this category are Cu, Zn, Ni, Co, As, Sb, Mo, and possibly Bi. Native Au, forming particles from the submicroscopic ranging to 1 or 2 mm sized crystals, can also be closely associated with goethite in lateritic duricrusts developed in the vicinity of bedrock gold mineralization. Gold complexes (Butt 1987), being transported through water saturated saprolite, would be readily broken down by the oxidation of ferrous iron, precipitating as goethite (B.H. Smith 1987; Webster and Mann 1984).

The component parts of lateritic duricrusts have different characteristics that are important in their use as sample media in geochemical exploration. Choices can be made depending upon the exploration purpose, namely, whether sampling for reconnaissance, fill-in reconnaissance, or for locating, in detail, the strongest part of a duricrust anomaly. For brevity, only four types of sample are mentioned here. Three of these relate to landform situations where a near-complete lateritic weathering profile is preserved, landform situations A and B of Butt and Smith (1980).

To a large extent, much of the outcrop-scale morphology of lateritic duricrust can be independent of local bedrock variation, the regolith units described below occurring on a variety of greenstone belt and granitic lithologies in the Yilgarn Block.

UNIFORM, PISOLITIC, FRAMEWORK-SUPPORTED LATERITE

This material (A in Figure 27.2) is the equivalent of that in Photo 27.1b with the irregular-shaped, lateritic nodules removed. Such material is typical of the upper part of pisolitic/nodular blankets and, where tested, can show a high degree of uniformity in geochemical characteristics. Mechanical dispersion is greatest in this part of the blanket, of

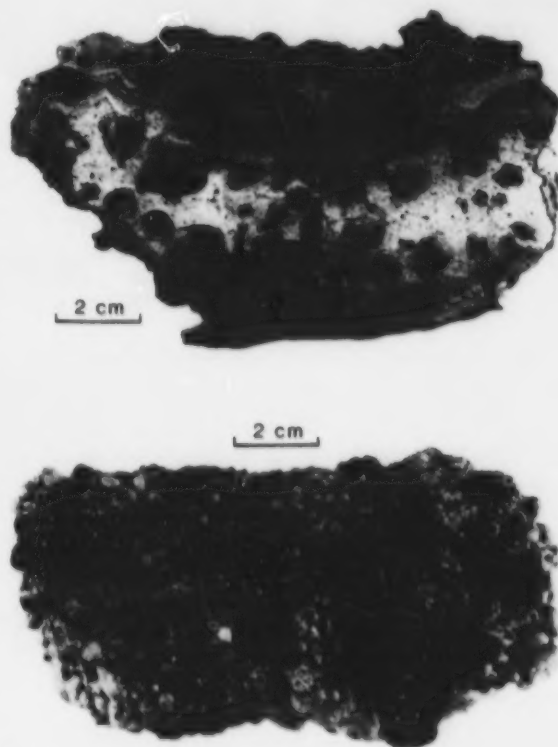


Photo 27.1. Handspecimens of two types of common lateritic duricrust residuums from the Yilgarn Block. a) sample from the mottled zone of Figure 27.2, showing lateritic nodules separated by a sandy clay matrix. b) the nodular, lower part of the pisolitic laterite of Figure 27.2.

kilometre scale at Golden Grove, for example (Smith and Perdrix 1983), and possibly several kilometres at Greenbushes (Smith *et al.*, in press). Sampling this material is most appropriate in reconnaissance exploration.

NODULAR, FRAMEWORK-SUPPORTED LATERITE

Photo 27.1b shows the handspecimen appearance of this material. Even the irregularly shaped nodules have subrounded extremities and well-developed concretionary skins (or cortices). No matrix is present in the example illustrated and the individual pisolites and nodules are lightly cemented together where they touch by pale brown gibbsite, identical to the concretionary coatings. This nodular material is typical of the lower part of framework-supported duricrust (B in Figure 27.2). Mechanical dispersion is often over some hundreds of metres rather than tens of metres. This material is a useful sample medium for the intermediate follow-up stages of anomaly delineation.

NODULAR, MOTTLED, MATRIX-SUPPORTED LATERITE

This type of duricrust material, shown in Photo 27.1a, and located in the profile (C in Figure 27.2), is interpreted to involve local mechanical movement over distances of tens of metres rather than hundreds of metres. This is concluded from isolated exposures which contain, fortuitously, quartz veins and show the displacement of the disaggregated quartz fragments in the laterite. Matrix-supported nodular laterite from the lower part of the duricrust is useful when tracing the source of an already identified duricrust anomaly.

LATERITIC COLLUVIAL-ALLUVIAL HARDPAN

Lateritic debris, including pisolites, nodules, and ferruginized rock fragments, can be included in colluvial-alluvial sheets at times overlying saprolite, other times overlying pisolitic and nodular laterite. Such material is a hardpan in the sense of Bettenay and Churchward (1974) and typically can have siliceous, ferruginous, and clay cements. This material has been used as a sample medium to delineate concealed bedrock Au mineralization (using Au, As, Sb, Bi, Ag and W, unpublished data). Interpretation of geochemical results, however, depends upon adequate knowledge of the lateritic regolith stratigraphy, a topic discussed below.

USE OF LATERITE GEOCHEMISTRY IN EXPLORATION

Hydromorphic dispersion is independent of mechanical dispersion; however, both processes are commonly involved in duricrust formation. It requires special conditions to be able to separate, for example, hydromorphic dispersion of As without any mechanical dispersion, from mechanical dispersion of goethite that already held hydromorphically dispersed As. In practice, most haloes in lateritic duricrusts, shown diagrammatically in Figure 27.3, are a combination of mechanical, residual, and hydromorphic dispersion.

The combination of these processes, inherent in laterite formation in general, tends to smooth much of the local chemical and mineralogical variation arising from changes of bedrock type (Figure 27.4). Observations show that the ability to use this smoothing effect to advantage varies from element to element depending upon the siting of the element (whether evenly dispersed within the sample or heterogeneously sited), the dispersion mechanisms, abundance level, anomaly contrast, and the mass of the sample.

Arsenic, a very useful chalcophile pathfinder for many classes of ore deposits (Boyle 1974), shows a relatively high level of geochemical homogeneity in pisolitic/nodular lateritic duricrust when kilogram-sized samples are taken. This is a function of its reasonable abundance level in laterites (commonly 10 to 30 ppm levels which are readily analyzed), its

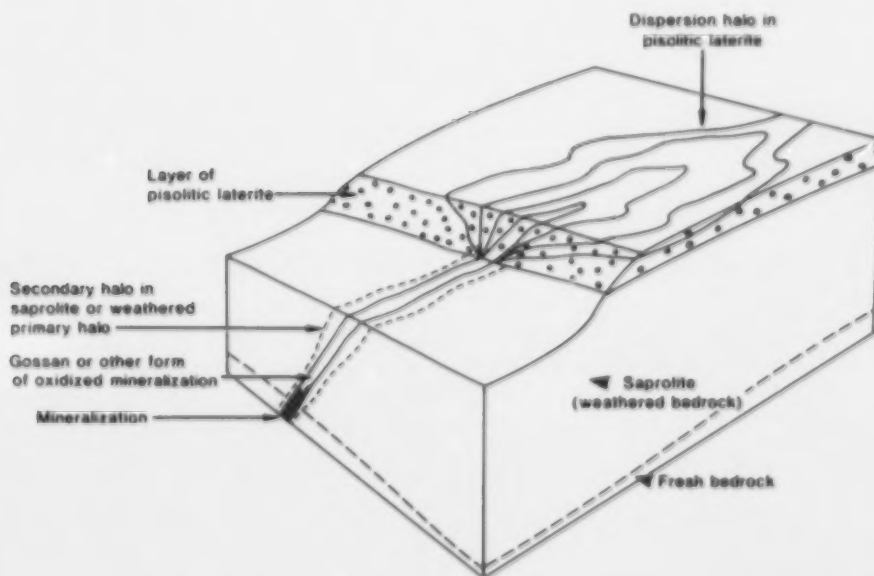


Figure 27.3. Block diagram showing idealized geochemical dispersion (mechanical, hydromorphic, and residual) from gossan or oxidized mineralization at the interface of saprolite against the overlying pisolitic laterite duricrust from R.E. Smith (1987b). Reproduced with the kind permission of Elsevier Science Publishers from the *Journal of Geochemical Exploration*.

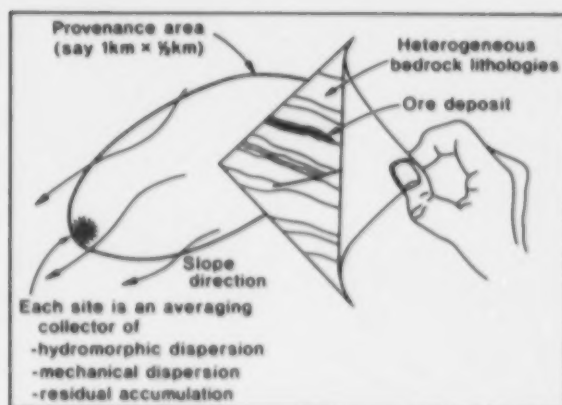


Figure 27.4. Because of hydromorphic and mechanical dispersion, and residual accumulation over long periods of time (say 1 to 10 million years), residuums on lateritic surfaces can be useful sample media, smoothing much of the local bedrock variation, as diagrammatically shown here.

ability to disperse hydromorphically during laterite formation, and its characteristic of being generally dispersed within the Fe-oxyhydroxides. In contrast, Au has a much lower level of abundance (a few ppb as background) and occurs typically as particles of native gold. Not surprisingly, therefore, the geochemical patterns observed for Au in laterite geochemistry can at times tend to be erratic, and the comments made by Radford (1987) are very relevant.

TARGET TYPES SUITABLE TO LATERITE GEOCHEMISTRY

An alphabetical list of elements that accompany various types of mineral deposits and that have been observed to form geochemical haloes in lateritic duricrusts include: Ag, As, Au, B, Ba, Be, Bi, Co, Cr, Cu, Ga, Ge, In, Li, Mo, Ni, Nb, Sb, Se, Sn, Ta, Te, W and Zn. To this one could probably add Pb. Furthermore, one would expect that Pt and Pd would be typomorphic indicators of Pt deposits though few data seem to be available. (References for this list of elements include: Mazzucchelli and James 1966; Smith and Perdrix 1983; Davy and El-Ansary 1986; Smith *et al.*, in press; Zeegers 1988; and experiences within the CSIRO Laterite Geochemistry Research Group). This list covers indicator elements from many types of mineral deposits (see for example the summary, Table 2 in Smith and Hallberg 1983).

Because of this wide spectrum of elements coupled with the often kilometre-sized haloes, laterite geochemistry is being used increasingly for multi-commodity resource appraisal as well as for the cur-

rent high level of gold exploration for which Au is typically supplemented by analysis of chalcophile trace elements.

Disseminated mineral deposits within plutons or stocks can form ideal targets for relatively low-density laterite reconnaissance geochemistry. For example, 3 km spaced sampling of laterites over parts of the Yilgarn Block led to the recognition of a series of specialized (Sn- and F-bearing) granites based upon As, Sb, Sn, and Nb haloes (unpublished data). Large pegmatite systems are also suitable candidates for low density laterite sampling, as shown by Smith *et al.*, (in press), with the multi-element halo about the Greenbushes pegmatite system measuring some 20 km by 12 km.

Polymetallic base metal sulphide deposits of 10 to 20 million tonnes or more form targets amenable to 1 km spaced laterite sampling for reconnaissance. Smith and Perdrix (1983) showed that although Cu, Zn, and Pb were weakly anomalous in pisolitic laterite, kilometre-sized haloes particularly for Bi, Sn, As, and Sb occurred in pisolitic and nodular laterite about the Golden Grove deposits, including the concealed and blind Scuddles deposit. Base metal sulphide deposits are very suitable for detection by laterite geochemistry and are particularly attractive exploration targets because of the possibility of carrying Au credits.

Metamorphogenic Au deposits, with their relationship to shear zones, quartz veins and stockworks, are common exploration targets in Archean greenstone belts. Subvertically dipping individual shoots may measure as little as 200 m by 5 to 10 m, a relatively small target. By using to advantage secondary dispersion in lateritic duricrust, sample spacings can typically range from 400 m to 1000 m. It is possible to also use to advantage any chalcophile envelope as a broader intermediate target than the deposit itself. Epithermal Au deposits generally have a useful chalcophile suite of accompanying elements and are quite amenable to laterite geochemical techniques. Sampling patterns depend upon size and geometry of the system.

Within the Yilgarn Block, multi-element laterite geochemistry is being widely applied and has led, or contributed, to the discovery of several important Au deposits. These include the Bottle Creek Au-Ag deposit (Govett 1987; Legge *et al.*, in press), and the Johnston Range Au deposits where reconnaissance was based upon 3 km spaced laterite sampling (as yet unpublished data). Both of these were "greenfield" discoveries.

Simpler approaches to laterite geochemistry, for example using Au analyses alone or supplemented by As and W, have also been particularly successful, leading to the discovery of several lateritic Au deposits, at times accompanied by economic saprolite, supergene and bedrock Au reserves (e.g. Glasson *et al.*, in press).

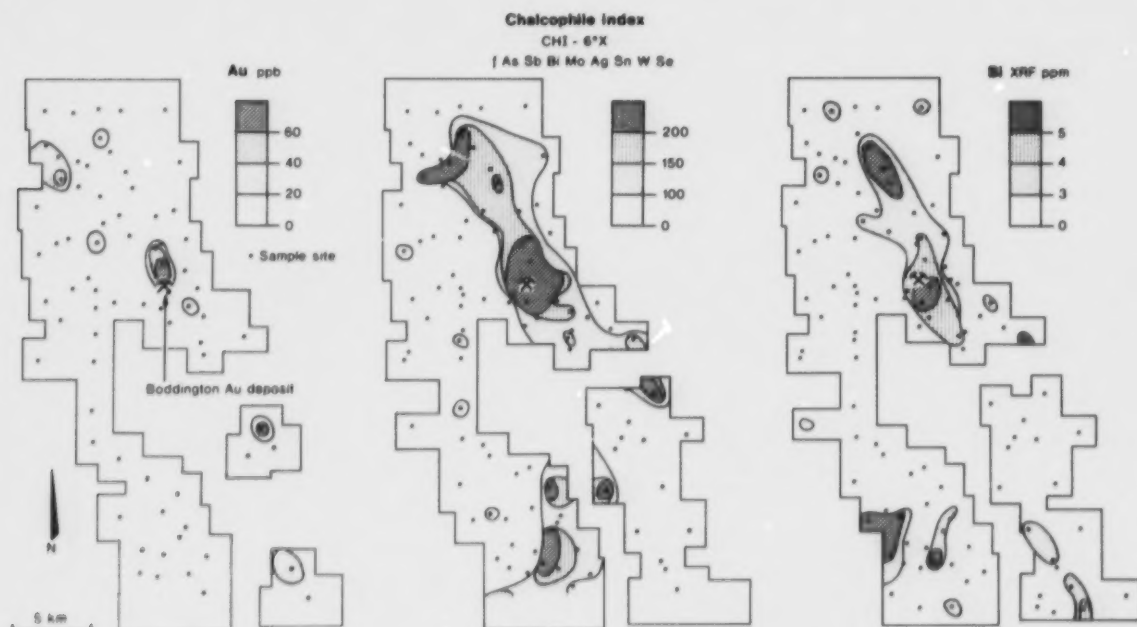


Figure 27.5. Reconnaissance laterite geochemistry over the Saddleback Greenstone Belt, Western Australia, showing dispersion patterns about the Boddington Au deposit, see text (from Smith *et al.*, in preparation).

In some studied examples, the chalcophile trace element dispersion halo in laterite may be much larger and more consistent than the halo for Au alone. This is the situation at Boddington (Figure 27.5), where laterite, saprolite, and supergene reserves exceed 45 million tonnes at 1.8 g/t Au (Monti 1987). The chalcophile halo in surface pisolitic laterite measures some 30 km by 4 km, compared with some 3 km by 1 km for the surface halo for Au in pisolitic laterite using a threshold of 40 ppb. At Boddington, the shallowest Au reserves are subsurface, perhaps reflecting downward mobility of Au, after laterite formation (Monti 1987), in response to the relatively high rainfall (Figure 27.6).

ROCK TYPE PREDICTION

Besides Si, Al, and Ga, the transition elements Fe, Ti, Mn, Cr, V, Ni, and Zr can be very useful in prediction of bedrock type from laterite geochemistry. Whilst simple level-of-abundance maps at times can be useful, bedrock prediction generally requires the use of multivariate statistical techniques. Discriminant procedures based upon the setting up of reference groups provide powerful tools for this task.

REGIONAL GEOCHEMICAL FEATURES

The ability of lateritic duricrust materials to provide a smoothed sample of geochemical variation can also be used to reveal geochemical features on a regional scale (Smith *et al.*, in press). In their study,

they recognized "chalcophile corridors", based largely upon As and Sb trends which cross the Yilgarn Block. These corridors are typically 15 to 30 km wide, can extend for 150 km, and appear to be of exploration significance because they link and enclose several important types of mineral deposits.

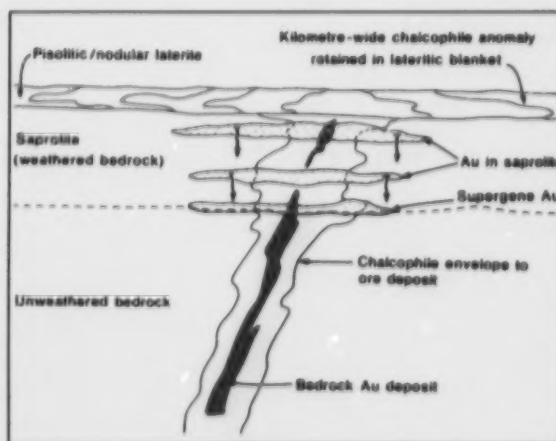


Figure 27.6. Diagrammatic cross-section depicting retention of chalcophile elements such as As, Sb, Bi, In, Mo, and perhaps Ge in the Fe-oxyhydroxides and Sn and W in resistant minerals in lateritic duricrust, whereas Au has undergone leaching and supergene enrichment during post-laterite modification of the weathering profile.

SAMPLING PATTERNS AND ANOMALY FOLLOW-UP

As with other forms of geochemical exploration, it is desirable to confine, as much as practical, belts of prospective terrain using regional geophysical surveys (gravity, airborne magnetics) where they are available, together with regional or district-scale geological mapping. In lateritic regions outcrop of even weathered bedrock, however, can be scarce, thus limiting bedrock information. It is in such terrain that secondary dispersion inherent in lateritic weathering can be used to great advantage. Laterite geochemistry has now evolved to the extent that areas completely covered with lateritic duricrust can be very effectively and economically explored. Somewhat ironically, such areas can now be a lot more economically assessed for mineral resources than many better outcropping regions of mixed exposure, thin soil cover, and thin patches of alluvium.

Where large-sized deposits are anticipated, reconnaissance sampling of lateritic duricrust can commence with sampling on a 3 km spaced grid. Triangular spacing of samples is generally used because it is efficient where dips are unknown or are variable, or where the targets are likely to be equidimensional. This pattern of sampling also allows efficient closing of sampling where follow-up is warranted. Where more intense sampling can be justified at the outset, 0.5 to 1 km spacing can be appropriate, as mentioned above.

Anomaly delineation typically uses fill-in sampling at 300 m spacing. In further follow-up stages, the basal lateritic duricrust is sampled in order to define the source of the duricrust anomaly. Sampling at 100 m spacing usually is sufficient, perhaps with several closer-spaced samples within the area. A proximity index, adding the number of anomalous typomorphic elements at each site, can be very effective at this stage (Smith *et al.*, in press).

Assessment of the local landform/regolith situation is generally critical for location of the anomaly source. Petrological and mineralogical study of laterite samples from the strongest parts of geochemical anomalies can be effective. Scanning electron microscopy can be invaluable for locating sites of heavy metals by images in the backscattered electron mode where brightness is a function of average atomic number in each mineral (Robinson and Nickel 1979).

Seeking a bedrock explanation of lateritic duricrust anomalies usually first involves use of rotary air-blast drilling into saprolite. In Au exploration, it is usually essential, for some of the holes at least, to penetrate and sample the whole saprolite profile, since Au may have undergone leaching from the upper saprolite coupled with supergene enrichment lower down, Figure 27.6. Drilling tactics can vary according to the geological/geochemical purpose (B.H. Smith 1987). Further stages of testing

involve angled reverse-circulation percussion, air core, and diamond drilling where warranted through the unweathered bedrock (Barnes 1987).

PRESENT LIMITATIONS TO LATERITE GEOCHEMISTRY

Although laterite geochemistry is being applied widely, the main limitations to growth potential are:

- Lower detection limits for Sb, Bi, In, Mo, Sn, W, Se, Te, Tl need to be reliably attainable on a routine basis, for example in the 10 ppb range. This would probably provide a wealth of pertinent geochemical information.
- Suitably clean, metal-free sample preparation is not yet widely offered by analytical laboratories. This is surprising since all the apparatus is available.
- Recognition of the sample type is critical and it can be difficult to distinguish between different regolith units, particularly in reverse circulation drilling spoil.
- There is a need for numerous case studies comparing sample media and showing dispersion characteristics under various landform and climatic conditions, for a variety of ore deposit types, to guide interpretation.

OUTLOOK

With reference to the landform and regolith situations shown in Figure 27.7, exploration understandably commences in the areas of outcropping bedrock (1). This is the realm of gossan geochemistry, the main thrust of exploration in lateritic terrain in Australia in the late 1970s. As laterite geochemistry became established, exploration for deposits concealed beneath a surface or near-surface duricrust took hold (situation 2). In Australia this was in the early to mid 1980s. For some countries this phase has not yet started, and can be expected to start in the near future.

Situation (3) depicts the lateritic blanket beneath sandplain. Where the lateritic duricrust material is less than about 1 m beneath the surface, sampling is easily executed at the same time as situation (2). Penetrating deeper sands in order to sample the duricrust may require use of a power auger, a backhoe, or perhaps sampling can be via termitaries.

Where exploration is advanced, attention progresses to situation 4, as currently happening in parts of Australia. Situation 5 seems to be little recognized or appreciated.

The area of concealment, in Figure 27.7 situations (2), (3), (4), and (5), in many lateritic regions, far outweighs the outcropping areas. Hence, many ore deposit discoveries can be anticipated with the increasing application of laterite geochemical techniques to such terrain.

Areas for which a lateritic duricrust is developed and preserved have become relatively easy to ex-

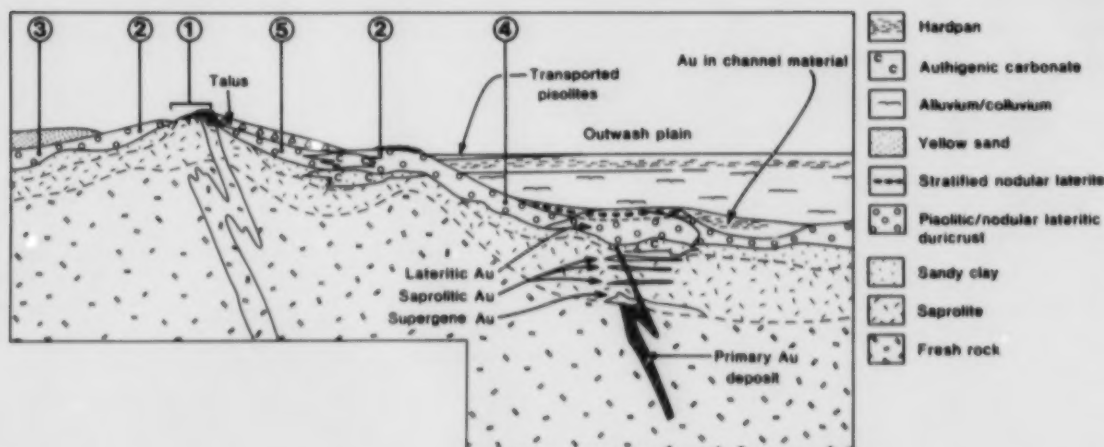


Figure 27.7. Cross-sectional synthesis of lateritic regolith stratigraphy typifying parts of the central Yilgarn Block, Australia, see text. Historically, exploration normally commences in situation 1, progressing through to situations 4 and 5.

plore provided the most appropriate material can be sampled correctly, and sample preparation, chemical analysis, and interpretation are correctly executed. The ability to explore these areas efficiently has been made possible because of the unique characteristics of lateritic weathering materials.

Driven by the expectation of discoveries of laterite, saprolite, and supergene gold deposits, as well as the search for concealed bedrock deposits, one can see major attacks being mounted on establishing and understanding the Cainozoic regolith stratigraphy of lateritic terrains. This has already started in Australia, and one can foresee this approach extending elsewhere over the next three to five years. This will parallel the advances since the 1960s made in Quaternary stratigraphy in glaciated terrain (Shilts 1984; see Paper 30, this volume). Cross-fertilization of glacial terrain techniques and approaches with studies in lateritic terrain should accelerate progress.

Research will establish the relative merits of different types of regolith units as sample media for geochemical exploration. With the high tempo of exploration in the mid 1980s, industry is quick to adopt progress.

Application of new or improved analytical techniques will impact upon laterite geochemistry where relevant improvements in lower limits of detection are made, as well as improvements in reliability, cost effectiveness, and turn-around.

Where appropriate, exploration programmes can use to advantage the analysis of some 30 elements in routine laterite geochemistry. This approach, started in the early 1980s, will progressively become widely used as our interpretational ability improves. More powerful procedures, particularly in anomaly recognition and characterization, will result as experience

in testing and applying multivariate statistical techniques accrues.

Interpretation of geochemical results will become more reliable and more diagnostic as the understanding of dispersion processes, bonding of elements, and evolution of landscape progresses.

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EXPLORATION '87 PROCEEDINGS

GEOCHEMICAL METHODS: THEIR APPLICATION TO ORE EXPLORATION

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28. Geomorphology and Climatic History – Keys to Understanding Geochemical Dispersion in Deeply Weathered Terrains, Exemplified by Gold

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ABSTRACT

Despite their present climatic diversity, large tracts of the continental landmasses between latitudes 35°S and 35°N have similarities of significance for geochemical exploration. These landmasses have all been tectonically stable and have had some important climatic and weathering episodes in common. In particular, they were subjected to seasonally humid tropical climates, broadly similar to those of the present-day wetter savannas, resulting in the development of an intensely weathered, leached, and commonly lateritic regolith, and marked planation of the landscape. Such conditions were geographically widespread from the Cretaceous to the mid-Tertiary, but later contracted to their present near-equatorial distribution. The development and presence of this regolith has had a profound influence on the mechanisms of geochemical dispersion and the surface expression of mineralization. Many geomorphological and geochemical characteristics of this earlier weathering are retained and, are commonly dominant, although modified under the influence of more recent climatic and tectonic changes. Accordingly, geochemical dispersion models can be developed to compare and contrast the surface expression of mineralization under present-day arid, savanna, and equatorial environments. Essentially similar models can be used to describe the genesis of some secondary ore deposits within these regoliths. The formation of lateritic and supergene gold mineralization is used as an example.

INTRODUCTION

Climate determines the active processes of weathering and erosion that are important in geochemical dispersion; these are expressed not only as soils and weathering profiles, but also as landforms. The climate of the soil is of the most relevance since it responds to very local influences such as slope and drainage, but atmospheric climate, for which data are far more abundant, is a good guide on a regional basis. The principal elements of the atmospheric climate that have the most influence on weathering are temperature and moisture, which are determined by geographical factors such as the relative distribution of continents and oceans, latitude, altitude, physiography, and aspect. Temperature influences the rates of chemical reactions, which increase by factors of

about two or three with every 10°C rise. Moisture is involved in most chemical reactions, either as a reagent itself or as the medium in which both reagents and products are transported and react, and for its role in physical erosion.

Soils characteristic of a climate may develop in 10² to 10³ years, deep weathering profiles in 10⁶ years (Nahon 1986) and landscapes in 10⁷ years (Budel 1982). However, climates have changed frequently and often quite profoundly over this period so that different dispersion processes will have been operating at different times. These are recorded as regoliths and landforms that are not in equilibrium with the present climatic conditions. In general, only the more recent, extreme, or older, longer-established climatic episodes will have left pedological or geomorphological records of significance. In the high latitudes, which at present mostly have temperate climates, these records are dominated by the effects of Pleistocene glaciation and its aftermath. In the middle and lower latitudes which now, mostly have sub-tropical and tropical climates, the regolith and landforms, particularly of continental areas of low relief, are an expression of the cumulative effects of subaerial weathering that has continued for tens or hundreds of millions of years. Northern parts of the Precambrian Shield of Western Australia, for example, may have been exposed to subaerial conditions since the Middle or Upper Proterozoic (Daniels 1975), with some of the iron ores of the Hamersley region being products of deep supergene weathering about 1800 Ma ago (Morris 1980). Consequently, recognition of the effects of past climatic and weathering episodes, as expressed in relic regoliths and landforms, is essential in interpreting geochemical dispersion in such terrains.

GEOMORPHOLOGY AND GEOCHEMICAL EXPLORATION MODELS

The importance of past climatic and weathering episodes in the development of landscapes has been recognized in studies of climatic geomorphology (Tricart and Cailleux 1972; Budel 1982). Regions that have broadly similar histories of weathering and landform development may be referred to as morphoclimatic or morphogenetic zones – the zones being defined in terms of the effects of active geomorphic processes on pre-existing regoliths and relief elements. Such a concept is a suitable basis for de-

TABLE 28.1. PRINCIPAL GROUPINGS OF GEOCHEMICAL EXPLORATION MODELS.

GLACIATED TERRAINS.		
Dispersion influenced by effects of Pleistocene glaciation		
<i>Present climate</i>	<i>Past climates</i>	<i>Morphoclimatic zones</i>
Glacial	Glacial	Polar, periglacial
Temperate	Glacial	Periglacial, boreal
Mediterranean	Temperate, glacial	Boreal
TROPICALLY WEATHERED TERRAINS.		
Dispersion influenced by effects of deep tropical weathering		
<i>Present climate</i>	<i>Past climates</i>	<i>Morphoclimatic zones</i>
Mediterranean/ subtropical	Savanna	Sub-tropical
Warm arid	Savanna	Warm arid
Savanna	Savanna	Peritropical
	Arid, savanna	Peritropical
	Rain forest, savanna	Peritropical
Rain forest	Savanna	Inner tropical
	Rain forest	Inner tropical
EROSIONAL AND YOUTHFUL TERRAINS.		
Dispersion influenced by effects of present climate		
Models classified according to climatic zone and relief.		

veloping geochemical exploration models and follows the principles of landscape geochemistry (Forstue 1975) that have been used to establish such models for some specific geographical and geological areas (Bradshaw 1975; Lovering and McCarthy 1978; Butt and Smith 1980). Three broad groups of models may be envisaged (Table 28.1). Two of these groups recognize that glaciation and tropical deep weathering, respectively, are the most important agents of geochemical dispersion and that the presence of regolith materials derived from either source has a dominating effect on geochemical dispersion. These groups apply particularly to regions of low relief. The third group refers to environments in which pre-existing regoliths are absent or of little significance, and dispersion is related only to the processes of the present environment. This group applies principally to erosional and youthful terrains, particularly those of high relief. An understanding of the geomorphology and, for the first two groups, climatic history, is thus essential for establishing geochemical dispersion models. The remaining discussion, however, considers only tropically weathered terrains.

Models based on the preservation of characteristics of deep weathering apply particularly to the continental landmasses between latitudes 35°N and 35°S, although similar features have been observed at much higher latitudes, in places beneath glacial overburden (Smith 1987). These regions were subjected to seasonally humid tropical climates, broadly similar to those of the present-day wetter savannas, resulting in an intensively weathered and leached regolith and marked planation of the landscape. Such conditions were probably geographically wide-

spread during the period from the Cretaceous or earlier until the mid-Tertiary, and subsequently contracted to their present near-equatorial distribution. Many geomorphological and geochemical characteristics of this early period have been retained, although they have been modified under the influence of more recent climatic and tectonic events. This has happened for two reasons. Firstly, the armouring effect of duricrusts helped preserve both the etchplain-inselberg relief and the deep regolith formed by such tropical weathering. Secondly, the chemical modifications resulting from changes in element mobilities due, for example, to different redox and drainage conditions, are commonly minor compared to the profound mineralogical and geochemical alterations that occurred during the original deep weathering. Model systems for these terrains are based on the presence of relics of this relief and regolith, and the effects (if any) of later physical and chemical modifications (Butt and Smith 1980; Butt 1985; Butt and Zeegers 1987).

MODEL SYSTEMS

Three systems of models can be derived:

- landform systems in which the pre-existing regolith profile is fully preserved
- landform systems in which the pre-existing regolith profile has been partly truncated
- landform systems from which the pre-existing regolith has been eroded.

In systems A and B, geochemical dispersion patterns comprise the effects of the earlier weathering episodes overprinted by those of currently active processes. In system C, dispersion patterns are solely

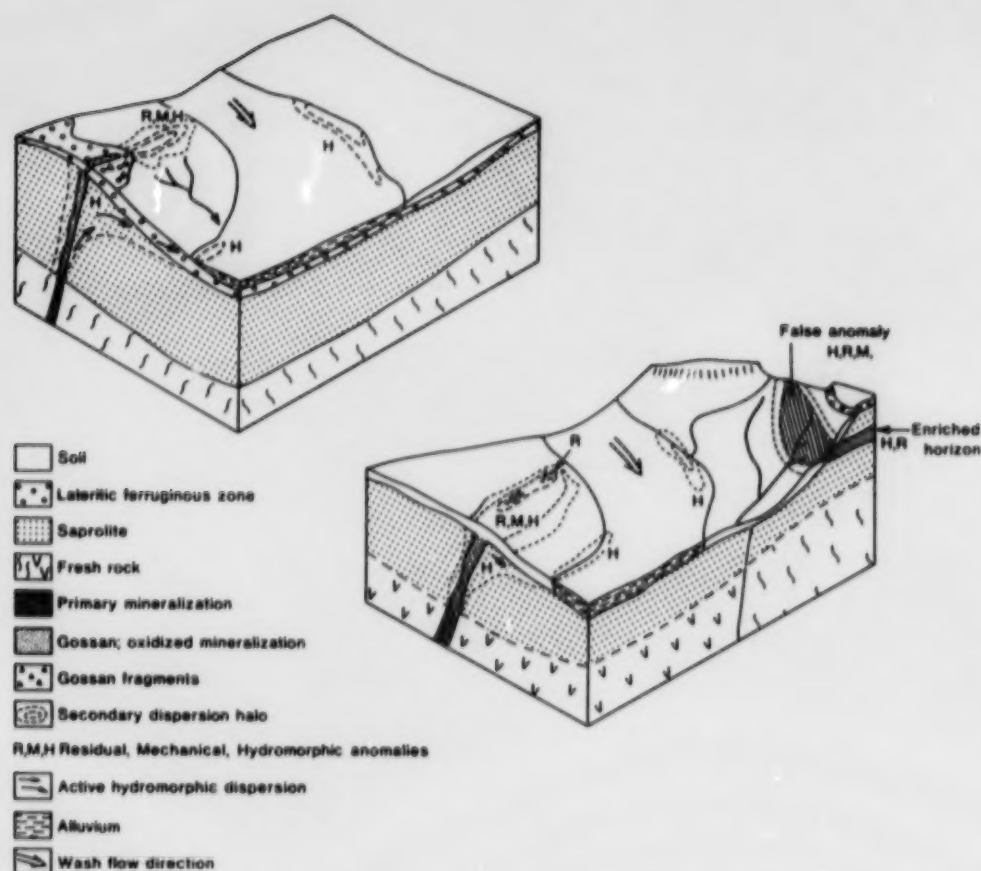


Figure 28.1. Generalized block diagrams illustrating some features of geochemical dispersion models for deeply weathered terrains in all climatic environments. A: weathering profile complete; B: weathering profile partly truncated.

the product of active processes. C-type models usually apply to only a small proportion of the landscape except in areas of moderate to high relief; in arid regions, there is usually little soil development and the present surface may have extensive outcrop corresponding to the earlier weathering front, perhaps with a veneer of transported overburden.

Block diagrams exemplifying landscapes and types of dispersion models appropriate to fully preserved and partly truncated regolith profiles (A and B above) are shown in Figure 28.1. In general terms, these apply to relevant situations in any climatic zone. They thus provide a means for comparing and contrasting the surface expression of mineralization under present-day arid, savanna, and equatorial environments. This extends the concepts upon which exploration of these areas may be planned and executed, by indicating appropriate sample media, predicting the nature of anomalies, and providing precedents for interpretation.

PROFILE FULLY PRESERVED

Where profiles are fully preserved, the upper saprolitic horizons are strongly leached, and lateral dispersion of most target and pathfinder elements is commonly very extensive, resulting in marked depletion of the elements and restricted anomalies. However, low-level but widespread anomalies may be present in the overlying lateritic ferruginous zone, either as pathfinder elements in resistant minerals, or as metals such as As, Au, Cu, and Mo bound to iron oxides.

Such anomalies are present in semiarid and seasonally humid (Mediterranean) regions of southwestern Australia. For example, Smith and Perdrix (1983) found that pisolite sampling at Golden Grove (semiarid climate) gave a clear expression of Cu-Zn mineralization. More or less coincident anomalies of greater than 250 ppm Cu, 100 ppm Zn, 200 ppm As, 20 ppm Sb, 60 ppm Bi, and 40 ppm Sn occur around a hill with outcropping gossans and iron-

stones (mean 950 ppm Cu, 140 ppm Zn, 95 ppm As, 55 ppm Sb, 60 ppm Bi and 80 ppm Sn). Most pisolites contain gossan fragments but Cu, Zn, and As are also concentrated in secondarily precipitated iron oxides that form concretionary rims to the pisolites. Where mineralization is subcropping, the anomalous response is confined to the pathfinders Bi, Sn, Se, Mo, Sb, and As, which possibly represent a weathered primary halo. In both instances, much of the dispersion has been detrital, either in gossan fragments or as resistant minerals such as cassiterite, and even on slopes as gentle as about 1:85 may extend for up to 1.5 km. Widespread anomalies also occur in lateritic pisolites around the Greenbushes Sn-Ta pegmatite deposit (Mediterranean climate) (Smith *et al.* 1987). These probably represent a mixture of primary haloes (including As, Sb, Li, B, and Sn), largely detrital secondary haloes (Sn, Nb, and Ta) that extend 1 to 5 km along gradients of 5 to 20 m per 1000 m, and hydromorphic reworking (As).

Equivalent responses are present in ferruginous laterites and associated soils in savanna climates. At the Goren deposit in Burkina Faso, Zeegers *et al.* (1980) found that over mineralization containing 0.2 to 0.3 percent Cu and 0.03 percent Mo, Cu is strongly depleted in the ferruginous laterite, though still anomalous, whereas the Mo content is similar. Both elements show lateral dispersion exceeding 300 m in the laterite and soils derived from it, using a threshold of 200 ppm Cu and 40 ppm Mo. The metal content of the soils tends to be lower, due to dilution and leaching during soil formation, but is preferred as the sample medium for logistical reasons. In the Betare Oya region of East Cameroon, Freyssinet *et al.* (1987) report lateral dispersion of 50 to 100 m in pisolitic laterite overlying sulphidic gold mineralization. Anomaly size is ranked as follows (threshold in ppm): Ag(0.2), Bi(5) < W(5), Pb(100), Mo(5) < Au (0.005), As(100). With the exception of Ag, which is strongly depleted, each element is only moderately leached relative to primary concentrations.

In savanna areas of East Africa, the extent of anomalies "preserved" in iron oxide nodules in relic lateritic profiles are supplemented by active hydromorphic dispersion into overlying aeolian sands (Brown 1970) and adjacent drainage channels. (Webb and Tooms 1959). Thus, the silt fraction and post-depositional nodules in Kalahari Sand are enriched in Cu, giving a surface expression to mineralization that is both deeply weathered and covered up to 30 m of transported overburden. The anomalies have low contrasts, with maxima of 60 to 100 ppm compared to a background of 20 to 30 ppm. Lateral migration within the Sand cover also gives detectable anomalies in seepages up to 1.5 km distant.

Ferruginous relics in the highly active, leaching environments of equatorial rain forests (in which the

cuirasse is being destroyed to form lateritic stone-lines), also give an anomalous response to underlying mineralization (see Lecomte 1983, 1988). For gold, dispersion during lateritization and subsequent reworking has resulted in significant anomalies (>0.2 ppm Au) in soils (Lecomte and Colin 1987).

PROFILES PARTLY TRUNCATED

Where profiles have been partly truncated in response to uplift or climatic change, the lateritic ferruginous zone is absent and different sample media have to be employed. Such truncation is advantageous where saprolite and bedrock are exposed for mapping, but elsewhere the erosion products remain as a cover of transported overburden. Exposure of gossans is of particular value and gossan search is an important procedure, especially in savannas and arid regions. However, ironstones of diverse origins may have similar geochemical characteristics, so that correct identification is vital. Similar criteria may be used for gossan evaluation in all these terrains, whether the present climate is arid, as in Saudi Arabia (Ryall and Taylor 1981); semiarid, as in Southern Africa (Andrew 1984) and Australia (Smith *et al.* 1982); or humid savanna, as in Kenya (Bugg 1982). Since the principal target (ore) elements may be leached from gossans or concentrated in secondary ironstones unrelated to mineralization, it is commonly necessary to rely upon the presence of suitable pathfinder elements for positive identification. Nickel sulphide exploration represents a particular challenge not only in gossan recognition (for which platinum group metal contents are commonly diagnostic) but also in distinguishing between those enrichments in saprolites due to sulphides and those due to weathering of silicate minerals of ultramafic host rocks. This problem applies to all deeply weathered terrains, whether profiles are complete or truncated; in the latter, lateritically enriched saprolites may outcrop or give rise to extensive soil anomalies.

Saprolites are the parent materials of recent residual soils in partly truncated terrains and, although less profoundly altered than were the overlying ferruginous zones, they may nevertheless be strongly leached, with anomalies of low intensity and showing little lateral dispersion. In arid environments, little further chemical differentiation occurs during pedogenesis, due both to the lack of water and the change from earlier neutral-to-acidic conditions to now prevailing alkalinity. Accordingly, the metal contents of soils commonly closely reflect those of the parent saprolite. The precipitation of pedogenic calcrete, however, may cause dilution of already weak anomalies, although the effect can be partly eliminated by preferential dissolution of the carbonate and analysis of the residue. Garnett *et al.* (1982) found that such a treatment enhanced the surface expression of the Putsberg copper deposit, South West Africa. The Cu content of some calcrete samples over mineralization increased from 100 to 200 ppm, to 150 to >500 ppm. However, the resul-

tant anomaly is still very restricted and for most samples the treatment seems to make little difference.

Not all elements are chemically immobile in arid climates or diluted by calcrete precipitation. Mo, U, V and, to some extent, As have significant mobility under alkaline conditions, and base metals (including Pb, Cu, and Zn) are soluble in saline groundwaters. Thus, in Western Australia, Mann (1983) reported concentrations of up to 2.1 ppm Pb, 0.3 ppm Zn and 0.24 ppm Cu dissolved in acidic, saline groundwaters; the metals are derived from the leaching of granitic country rock, unrelated to mineralization. Similarly, as discussed below, the post-lateritic mobility of Au is important in determining the surface expression of gold mineralization and the formation of supergene deposits in presently arid, deeply weathered terrains.

In humid environments, chemical processes are more active and geochemical anomalies tend to be broadened by hydromorphic dispersion, especially in the soil and upper saprolite, although the intensity of the anomalies will depend upon both the degree of truncation and the intensity of present leaching. In savannas in East Africa, for example, elements such as As, Co, Cu and Mo are retained in soils, associated with clays and ferruginous concretions, but can also show significant hydromorphic dispersion into seepages and swamps, thereby broadening anomalies considerably. Govett (1987) noted that in addition to the lateritic concentration of Cu (>500 ppm) over mineralization at Baluba, Zambia, higher levels (>2 000 ppm) occur 750 m away in organic soils in drainage channels (dambos). A higher proportion (over ten percent) of the Cu in the dambo soils is cold-extractable compared to the laterites (one percent), hence the enrichment in the dambos is probably due to active hydromorphic processes.

Even in the most strongly leached rainforest environments, soils may still retain the signature of underlying mineralization. However, residual anomalies may become dominated by the less mobile elements such as Pb and Bi; seepage anomalies seem less important than in savannas, although some hydromorphically dispersed metals may become adsorbed to organic matter and iron oxides in streams to give low order anomalies. As an example, in French Guiana, Laville-Timsit *et al.* (1983) found that the surface expression of the THR Pb-Zn deposit is dominated by Pb, which gives a soil anomaly of 200 x 600 m using a 200 ppm threshold. The Pb content declines from over 1000 ppm in the soils to 100 ppm in sediments from streams eroding the anomaly. In contrast, Zn is almost completely leached from the soils (<100 ppm), but is slightly enriched (>200 ppm) in stream sediments. Chemically mobile elements can be enriched in such ferrallitic soils, particularly in the "B horizons". In Guyana, Montgomery (1971) found that Cu and Mo concentrates in iron oxide nodules and mottles (e.g. 250 to 18 000 ppm Mo). However, although con-

centrations in the minus 80 mesh fraction of the soils are far lower (50 to 500 ppm Mo), soil sampling has logistical advantages for routine surveys. Similar conclusions were drawn by Zeegers (1979) in French Guiana and Matheis (1980) in Nigeria where, despite strong leaching, sampling of "B horizon" soils is effective for exploration and mapping purposes, even at reconnaissance scale grids of 1 x 1 km. (This scale is comparable to that advocated by Smith *et al.* (1987) for pisolite sampling in Western Australia).

FORMATION OF LATERITIC AND SUPERGENE GOLD DEPOSITS

The mechanisms of formation of lateritic and supergene gold deposits can be described by genetic models similarly based on geomorphology and climatic history. These deposits, at present the focus of much exploration and mining activity, are low grade enrichments of gold in ferruginous and saprolitic horizons of deeply weathered regoliths. They are known from all climatic zones, from extremely arid (Um Nabardi, Sudan (Fletcher 1985) to rain forest (Dondo Mubi, Gabon (Lecomte and Colin 1987) and are characterized by the secondary mobilization of gold from or within mineralized source units, including shear zones and associated alteration assemblages, to form:

1. more or less flat-lying enrichment zones contiguous with the ferruginous horizon and, commonly, the mottled zone, of the laterite profile (i.e. "lateritic gold deposits").
2. residual or absolute enrichments within saprolite (i.e. "supergene gold deposits"). In humid tropical regions, these enrichments are usually minor and confined to the weathered profile of the source unit. In present (or past) arid regions, there may be lateral dispersion into wall rocks, commonly as one or more subhorizontal zones; the upper saprolite of the source unit may also be markedly depleted in gold.

These gold distributions have occurred as a result of reactions of the type shown in Table 28.2 taking place selectively under the varied environments imposed by geomorphological and climatic changes (Baker 1978; Mann 1984a, 1984b; Webster and Mann 1984; Webster 1986; Stoffregen 1986). The similarities and differences between deposits in humid and arid areas are due to the similarity of the initial deep weathering and differences in the modifications imposed by later events. Possible mechanisms of formation are discussed below.

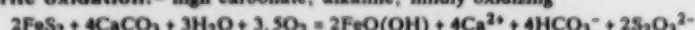
GOLD MOBILITY DURING LATERITIZATION

During lateritization in seasonally humid, tropical climates, oxidation at the weathering front deep below the water table produces neutral-to-acidic conditions, with lower pH favoured by felsic rocks and high sulphide contents. Gold associated with telu-

TABLE 28.2. GOLD SOLUTION AND PRECIPITATION MECHANISMS.

1 THIOSULPHATE COMPLEXES

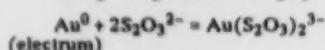
1A Pyrite oxidation: - high carbonate, alkaline, mildly oxidizing



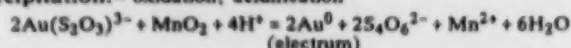
1B Pyrite oxidation: - low-moderate carbonate, mildly acid-mildly alkaline, oxidizing



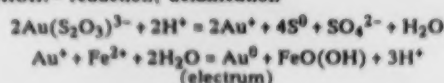
Gold dissolution



Gold Precipitation: - oxidation, acidification

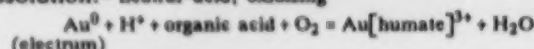


Gold Precipitation: - reduction, acidification

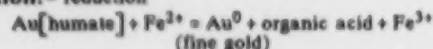


2 ORGANIC COMPLEXES

Gold dissolution: - neutral-acid, oxidizing

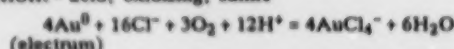


Gold precipitation: - reduction

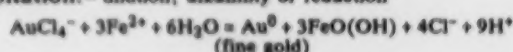


3 CHLORIDE COMPLEXES

Gold dissolution: - acid, oxidizing, saline



Gold precipitation: - dilution, alkalinity or reduction



rides or held in the lattice of the sulphides and other minerals may be released but the free metal remains largely immobile due to the absence of suitable complexing ligands. Concentrations of chloride ions and organic matter are very low and thiosulphate ions are formed only by sulphide oxidation in neutral-to-alkaline conditions. Accordingly, although some corrosion and reduction of size occurs, gold grains with high Ag contents (i.e. low-fineness, primary gold containing greater than two percent Ag) persist into the ferruginous zone (Lecomte and Colin 1987; Freyssinet and Zeegers 1987), and lateral dispersion into saprolitic wall rocks is minimal. Free gold (and silver) may be mobilized, however, if high concentrations of carbonate are present in the primary mineralization, because the oxidation of pyrite proceeds under an alkaline environment to produce thiosulphate (reaction 1A, Table 28.2). This mechanism has been invoked to explain the solution and reprecipitation of electrum in tropical, humid Papua-New Guinea (Webster and Mann 1984), although the high relief and free-draining, relatively thin regolith differs from lateritic conditions. Stof-

fregan (1986) suggested the possibility of solution and immediate re-precipitation of gold and silver by thiosulphate under near-neutral conditions, the principal effect being a reduction of grain size (reaction 1B, Table 28.2).

Lateral dispersion of gold is evident towards the top of the lateritic profile, particularly in the ferruginous and mottled horizons (Freyssinet *et al.* 1987; Michel 1987). This may be due in part to residual concentration and surface wash during landsurface reduction, and in part to mobility, either in solution or as colloids, complexed by humic acids produced by the rapid degradation of organic matter in soil (reaction 2, Table 28.2). Some gold may also be contributed directly to the soil in organic litter after uptake by plants. Reduction of the complexes by ferrous iron results in the incorporation fine-grained gold with low Ag contents in iron oxides in the ferruginous and mottled zones. Such mechanisms can account for the formation of the lateritic deposits, with their mixture of gold of both high and low fineness, that form widespread blankets over

relatively narrow, weathered, mineralized sources. The relative contributions of the physical and chemical mechanisms is uncertain, during both this and subsequent climatic episodes. The presence of outer zones of fine gold around some nuggets suggests the possibility that silver may be leached from small grains without the gold itself being dissolved, yielding a product of high fineness. Downward mechanical illuviation of gold particles is also possible.

The effects of climatic change in modifying this initial distribution can be demonstrated by a comparison of deposits in rain forest and arid environments.

GOLD MOBILITY IN RAIN FOREST ENVIRONMENTS

The effects of a change to more humid rain forest climate and some epeirogenic uplift are indicated in Figure 28.2. Under such conditions, the pre-existing profile is subject to increased leaching, ultimately forming stone-line profiles. Where there is little erosion, the stone-line is comprised of blocks of degraded lateritic cuirasse overlain by a strongly leached, friable soil 1 to 5 m thick. Previously formed lateritic enrichments of gold are retained in resistant cuirasse but may be leached from the soil, probably as gold-humate complexes. These either precipitate near the stone-line with neo-formed iron oxides, augmenting the enrichment due to the degraded laterite, or are removed entirely, perhaps to precipitate as placers in drainage channels. Similar leaching may affect lower horizons of the profile; the result is an absolute loss of gold and other elements, with no appreciable lateral dispersion halo being formed in the saprolite. At Dondo Mobi, Gabon, Lecomte and Colin (1987) found that gold was concentrated in these upper horizons by a factor of 3.5 compared to the saprolite, forming a "mushroom-shaped" surface enrichment halo. Soil sampling gave an anomaly 100 x 65 m, using a 0.2 ppm threshold, but extending at lower concentrations for over 500 m to link with placers in adjacent drainage channels. Within the main soil anomaly, the size of the gold particles declines, as a result of the etching of primary gold grains and precipitation of secondary grains.

Reactions at the weathering front are similar to those prevailing during lateritization. If the original profile is truncated by erosion, any lateritic enrichment is destroyed. Strong leaching and dispersion of gold again occurs in the soil, but there is no enrichment in the saprolite. Gold leached during lateritization and under rain forest conditions may contribute to the regeneration of some placer deposits (Boyle 1979); the placers at Dondo Mobi (see above) may be of this type, at least in part.

GOLD MOBILITY IN ARID ENVIRONMENTS

The effects of a change to a more arid climate, perhaps with some epeirogenic uplift, are shown in Figure 28.3. These changes cause a lowering of the water table so that upper horizons are progressively unsaturated; the pre-existing profile is subjected to decreased leaching and alkalis and alkaline earths are retained in the weathered profile. In winter rainfall regions, this is shown by the development of pedogenic calcrete. Evaporation exceeds precipitation so that sodium chloride and other salts, derived largely from rainfall, concentrate both in the unsaturated zone and in the groundwater. The mechanisms of gold mobilization change also. The decrease in vegetation greatly reduces the availability of humic complexes for gold mobility. More prevalent alkaline conditions increase the possibility of thiosulphate formation during sulphide oxidation, but the rate of weathering is mostly very slow. More significant, however, is the development of salinity, for this permits the formation of soluble gold chloride complexes (reaction 3, Table 28.2).

In the present warm arid zones, the change from a wet savanna climate has taken place since the mid-Tertiary or earlier. During this long period, several reversals to humid climates have occurred, restoring conditions conducive to deep weathering. Accordingly, the lowering of the water table would have been punctuated by stillstands or temporary rises. Such events have great significance, for under these circumstances, the increased rainfall leaches precipitated salts and recreates redox conditions suitable for ferrolysis, and thus produce acidic, saline and oxidizing groundwaters capable of dissolving gold (Mann 1984a). In the near-coastal Darling Range of Western Australia, for example, such conditions have developed in response to recent humidity and elsewhere have been mimicked by the rise in water table following clearing for agriculture. During these humid periods, therefore, gold may be dissolved and mobilized, to be re-precipitated with iron oxides by reduction by ferrous iron at the water table. Successive humid periods during the general lowering of the water table can account for the presence of two or three subhorizontal, supergene enrichments within the weathered source unit and in saprolitic wall rocks. Such enrichments are observed in numerous gold deposits in Western Australia, the best documented of which is Boddington (Davy and El-Ansary 1986; Monti 1987). Here, gold is concentrated in the lower part of the (bauxitic) laterite, within the middle of the kaolinitic saprolite and close to the weathering front, usually at about 40 m. It occurs as free grains of about five microns, and is mostly secondary. Lateral dispersion of gold exceeds 500 m in the lateritic horizon and a widespread multi-element anomaly (As, Cu, Sb, Mo, W) is indicated by pisolite sampling. Similar processes have probably formed equivalent enrichments elsewhere; a possible example is Um Nabardi, Sudan (Fletcher 1985).

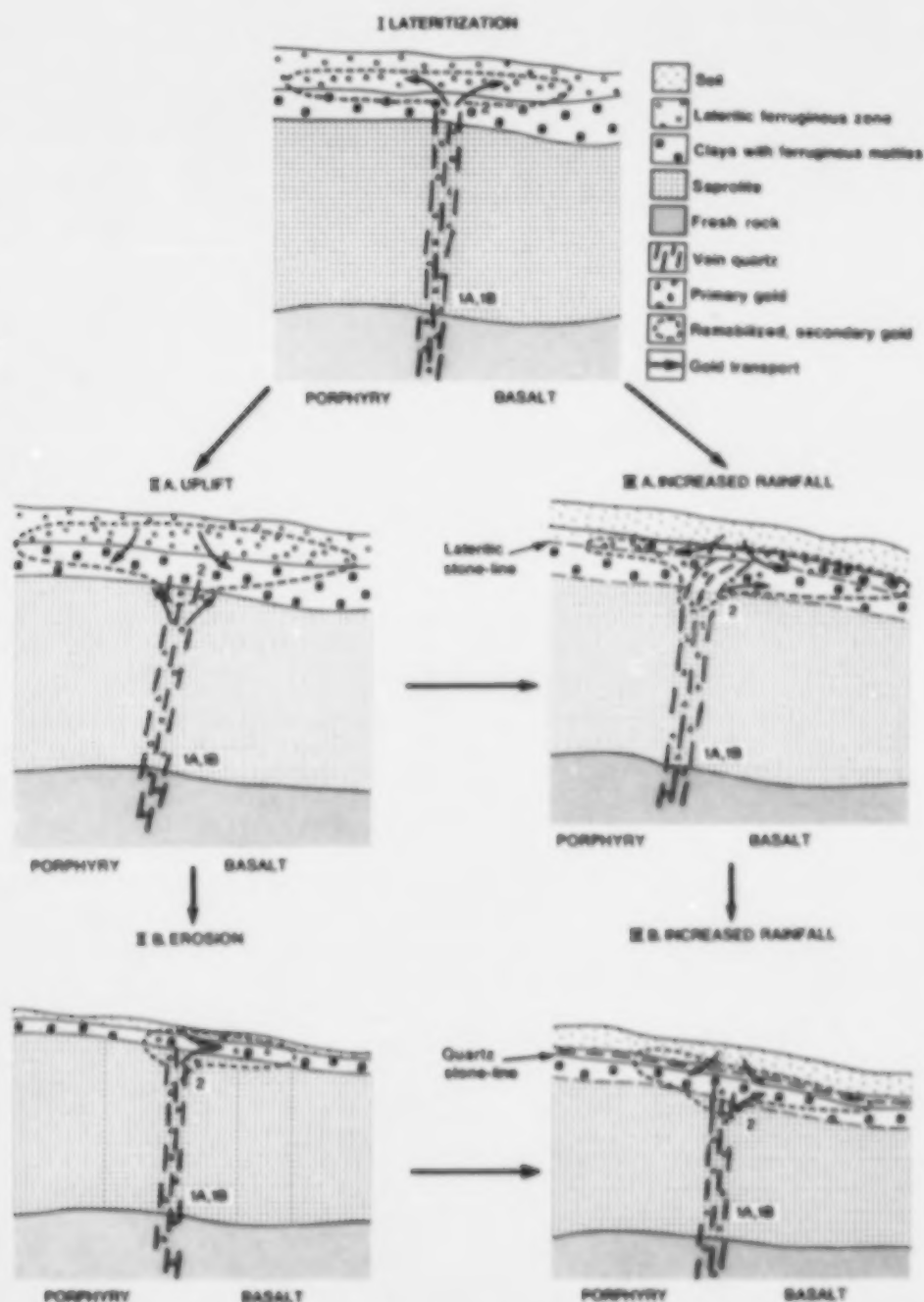


Figure 28.2. Model illustrating the modification of gold dispersion patterns as a result of uplift and a change to a rain forest climate. Numerals refer to possible gold mobilization reactions given in Table 28.2. See text for detailed description.

where gold enrichment is associated with the water table at 50 m in a deeply weathered profile.

Experiments by Mann (1984a, b) suggest that gold-silver alloys may be more soluble than pure gold. If this is so, primary gold could be preferen-

tially dissolved during this process and assisting the preservation of pre-existing lateritic enrichments. Additionally, the repeated strong leaching of the upper saprolite leads to a marked depletion of gold in the top 5 to 15 m of the mineralized unit. This mechanism operates even if the profile is truncated;

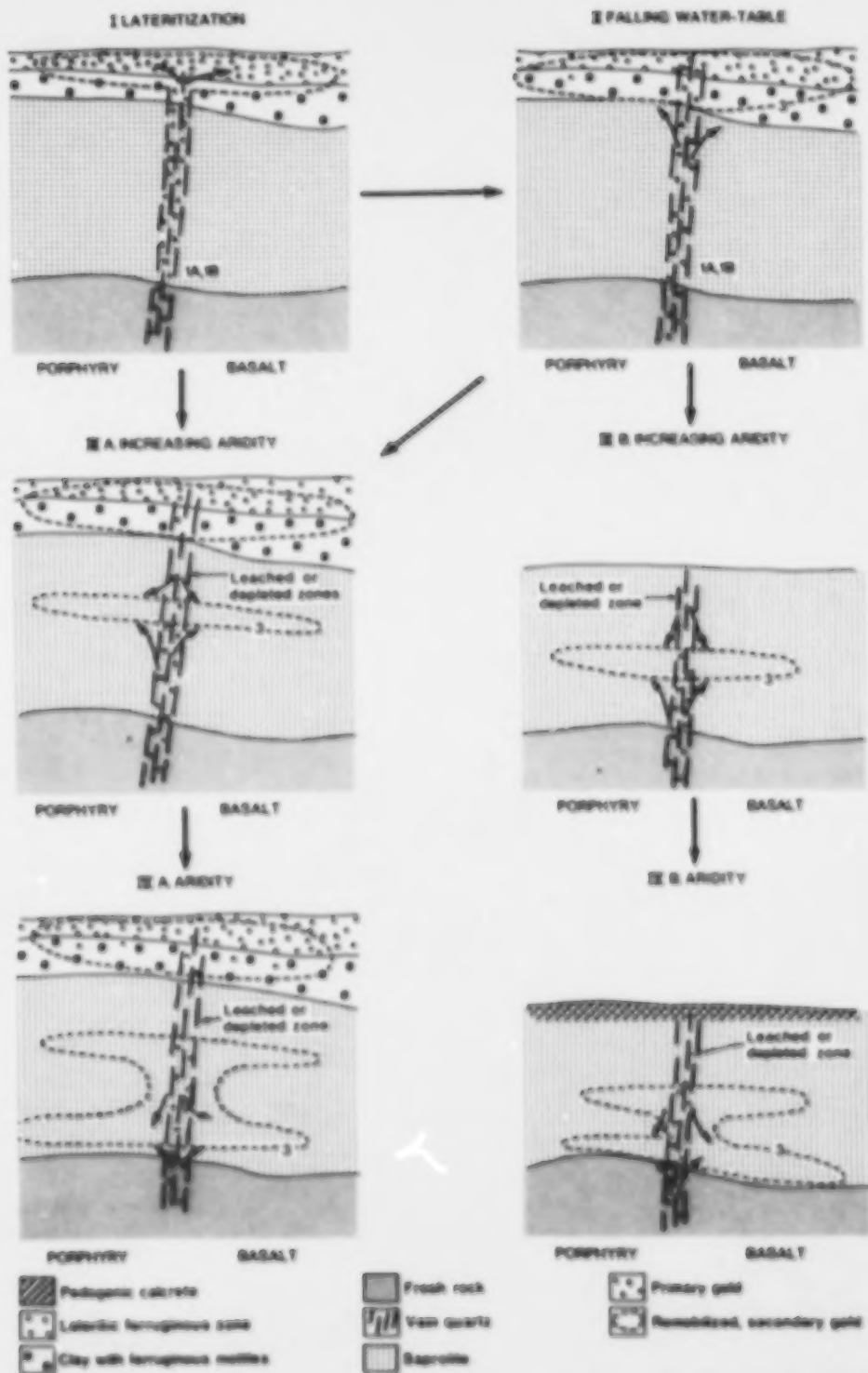


Figure 28.3. Model illustrating the modification of gold dispersion patterns as a result of uplift and a change to an arid climate. Numerals refer to possible gold mobilization reactions given in Table 28.2. See text for detailed description.

consequently, in the absence of lateritic enrichment, near-surface expression of the mineralization is minimal, giving rise to exploration problems. Mineralization may be indicated by pathfinder elements such as As, Sb, W and Bi, even though gold may be totally leached. Nevertheless, minor enrichment of gold (50 to >150 ppb) may be present in the soil, especially in pedogenic calcrete, which thus has potential as a sample medium even where there is transported overburden. Uptake of gold by plants, deposition in litter and fixation at the pH barrier of the calcrete is a possible mechanism.

SUMMARY AND CONCLUSIONS

In all but the most recently emergent or juvenile terrains, the present regolith is the product of weathering that has taken place under several climatic regimes. The longer the period of exposure to sub-aerial conditions, the more complex has been the climatic and weathering history. In the plateaux of the continental landmasses of the present tropics and subtropics (especially between 35°N and 35°S), this history commonly extends back to the Mesozoic or even earlier. During this period, there have been several major climatic changes and, together with contemporaneous tectonism, these have had profound effects on the geomorphology of the landscape and the nature and geochemistry of the regolith. A common feature of these regions has been the extensive planation of the landsurface and the development of a deeply weathered, mostly lateritic mantle, formed under tropical, humid savanna conditions. Subsequently, these have been physically and chemically modified under the influence of later climates. Comparisons between regions having differing climatic and weathering histories can demonstrate the conditions under which certain distribution patterns and enrichments were formed. By recognizing the geochemical consequences of the principal climatic and tectonic events, models can be derived to assist the interpretation of dispersion patterns within the regolith. Essentially similar models can describe the genesis of some secondary mineral deposits, not only those of gold, as discussed in this paper, but others such as nickel laterites and some bauxites that are the product of long-term weathering under changing conditions.

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GEOCHEMICAL METHODS: THEIR APPLICATION TO ORE EXPLORATION

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29. Geochemical Exploration in Areas of Glaciated Terrain: Geological Processes

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ABSTRACT

By understanding the processes of glacial erosion, transport, and deposition it is possible to improve the design of geochemical sampling and to interpret results better.

Erosion occurs at the glacier bed by abrasion and plucking. Abrasion occurs preferentially on the upglacier side of obstacles, produces the characteristic striation of glaciated terrain, and furnishes mainly silt to the glacial load. Plucking removes bedrock joint blocks particularly from the down-glacier side of obstacles. In addition to the products of abrasion and plucking, Alpine glaciers receive sediment from flanking slopes.

Transport plays an important role in the abrasion and crushing of clasts and largely determines the grain-size distributions of basally transported tills. Little glacial modification occurs of clasts trans-

ported englacially or supraglacially. In the simplest case, debris in transport found nearest the bed is the most locally derived, but folding and thrusting of the basal ice layers may alter this relationship.

Deposition of till by lodgement involves the production of large quantities of silt as clasts are abraded, and the constant ploughing and deformation of the substrate. Melt-out is more passive and the stratigraphy of the debris in the ice is preserved in the till. Deposition by debris flows or by sedimentation from floating ice produce till-like sediments which may be misinterpreted to give misleading impressions of glacial histories.

Complications may occur as a result of the influence of meltwater, multiple glacial advances, partial preservation of depositional suites, and subtle variation of glacial conditions with time. However, general awareness of the above processes should enhance exploration efficiency.

30. Geochemical Exploration in Glaciated Terrain: Geochemical Responses

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ABSTRACT

Mineral exploration in regions that were glaciated during the Quaternary period is hampered by the scarcity of outcrops and by the variable thicknesses of allochthonous glacial drift that mantle the bedrock. Geochemical strategies that have been successful in exploration usually involve an understanding of the history of the glaciated landscape.

The past decade has seen a substantial increase in our knowledge of glacial stratigraphy and associated ice flow directions. In many areas of thick drift, the glacial succession has been found to contain multiple tills having different provenances related to distinct ice flow directions. The use of drilling and trenching has been instrumental in providing data on the glacial succession. Of particular value has been the ability of sonic drills to recover intact core of the entire glacial sediment sequence. Light portable drills have been used similarly in areas of thin drift. The increased use of till geochemistry in mineral exploration and regional surveys has resulted in the discovery of several ore deposits and the documentation of many dispersal trains derived from mineralization and from distinctive bedrock units.

Stratigraphic drilling programs and major reconnaissance surveys of till geochemistry have provided baseline data for other geochemical data sets, mineral exploration, bedrock mapping and environmental studies. Data on surficial geology, glacial stratigraphy and ice flow directions have been collected to aid interpretation of the till geochemistry. Research on the residence sites of metals in till has indicated that specific grain size ranges and mineralogical forms hold the bulk of the metals, depending on the species of primary metal-bearing minerals and the history of glacial comminution and weathering.

INTRODUCTION

In regions that were glaciated during the Quaternary period, mineral exploration can be hampered by the complexity of the surficial sediments, which are largely allochthonous in relation to the bedrock they overlie. In the context of almost totally glaciated landscapes, which includes most of North America north of 40°N, Greenland and Iceland, most of Europe north of 50°N, extensive parts of Asia north of 60°N, parts of South America, and Antarctica; the sediments have particular characteristics that in-

fluence the selection of sample media, sampling design and interpretation of data. Foremost among these sediments is till or recycled derivatives of it. Till has distinctive provenance features; it is a first-cycle sediment, it is widespread, and it is parent material for most of the other surficial sediments.

Over the past decade (1977 to 1987) a large number of papers have been published on till geochemistry, boulder tracing, glacial dispersal trains, the history of ice flow patterns and glacial sediment stratigraphy as related to mineral exploration and regional till geochemical/Quaternary geology mapping programs. The bulk of this work has been carried out in Canada and Finland. This paper attempts to summarize the salient features and trends from these works (1977 to 1987) and follows on, to a degree, from the last review paper by Bolviken and Gleeson (1979) at Exploration '77. Our main sources have been the proceedings volumes from the biannual symposia on Prospecting in Areas of Glaciated Terrain (Institution of Mining and Metallurgy 1979, 1984, 1986; Davenport 1982), articles in scientific journals, in particular the *Journal of Geochemical Exploration*, and publications by government agencies. Although we have attempted to be as thorough as possible in reviewing the references of the past ten years, we have had to be selective and undoubtedly we have missed some articles. Our main objective is to familiarize the reader with the names of people working in a given geographic area or on a particular aspect of till geochemistry as applied to mineral exploration. The exploration geologist should also note that while a large portion of the baseline Quaternary geology maps, certainly in Canada, are being produced by many of the same people cited herein; only a small number of these maps, generally those with some component of geochemical data, are referred to in this article.

GLACIAL DISPERSAL

The nature of glacial dispersal and the resultant dispersal trains, particularly as related to mineral exploration, have been described in general by a number of authors in the last decade (e.g. Shilts 1976, 1982a, 1984a; Hirvas 1977; Minell 1978; Drake 1983; Miller 1984; Geological Surveys of Finland, Norway and Sweden 1986a, b, c, d, e, f; Salonen 1986a, b; DiLabio and Coker 1987; Strobel and Faure 1987; Clark 1987; and DiLabio, in press). During the Quaternary period till was produced by the glacial erosion, transport and deposition of fresh

and weathered unconsolidated sediments and bedrock. Till is therefore a geologically young sediment which at any given site is not an *in situ* weathering product but a lithological summation of source units up-ice from the site. Debris from any size of source unit is dispersed down-ice to produce a ribbon-shaped or fan-shaped dispersal train; a body of till that is enriched in debris from the source relative to the till surrounding the train. Shilts (1976) has shown that a plot of the abundance of glacially dispersed debris versus distance down-ice approximates a negative exponential curve (Figure 30.1), in which the concentration of a component reaches a peak near its source (i.e. the head) and then declines exponentially to background levels down-ice (i.e. the tail). Many dispersal trains have abrupt lateral edges, with sharp contrast over a short distance between low concentrations outside the train and high concentrations inside it. The tail is generally many times larger than the head and is generally the part of the dispersal train first detected by till sampling programs. Dispersal trains of distinctive boulders, minerals, trace and/or major elements, and radioactive components may enhance the size of mineral exploration targets by several orders of magnitude. A major objective of till geochemistry is simply to detect the tail of a dispersal train, trace it back to its head, and locate its source.

In glaciated terrain, the composition of a till sample may be the composite of many overlapping dispersal trains. The blending of trains derived from different up-ice sources produces the mixed lithol-

ogy that is a normal feature of till. Most of the individual dispersal trains are not identifiable, however, because they are too small or are composed of rocks or minerals that are not distinctive. The size and shape of the dispersal train are controlled by the orientation of the source relative to ice flow, by the size and erodibility of the source, and by the topography of the source and dispersal areas, which can trap trains in valleys and break them into disjointed segments, in rough terrain, or even truncate them.

Dispersal can occur at a variety of scales ranging from continental (hundreds of kilometres), to regional (hundreds to tens of kilometres), to local (less than ten kilometres), to small-scale (final stages of mineral exploration in the hundreds to tens of metres) (Shilts 1984a). Glacial dispersal trains exist that are up to hundreds of kilometres in length, such as the train of carbonate-rich till that extends southwards from Hudson Bay (Coker and Shilts 1979; Shilts *et al.* 1979; Shilts 1980; Geddes and Kristjansson 1986; Karrow and Geddes 1987; Kaszycki and DiLabio 1986a) and the train of debris derived from Dubawnt Group rocks that extends eastwards into and across northern Hudson Bay (Shilts *et al.* 1979; Shilts 1982b) (Figure 30.2). Other examples of major glacial dispersal patterns include those documented by Klassen (1984) and Klassen and Thompson (1987) in Labrador; Stea and O'Reilly (1982) in Nova Scotia; Dredge (1983a, b), and Kaszycki and DiLabio (1986a) in Manitoba; and Hyvarinen *et al.* (1973) and Salonen (1986a, b) in Finland. Trains of this size are detected only when the characteristic lithological component of the train is present in adequate amounts and is distinctive against the background rock types in the dispersal area. For drift prospecting purposes, these large trains are significant in that the exotic lithology of the till can mask the lithology and geochemistry of mineralized debris eroded from local sources (i.e. Geddes and Kristjansson 1986; Gleeson and Sheehan 1987). Large trains such as these can be detected by "reconnaissance" scale sampling, one till sample per 100 km².

Smaller dispersal trains derived from individual rock units, distinctive belts of rock, or mineralization are more likely to be detected in the preliminary stages of mineral exploration programs. At this stage of exploration, "local" scale sampling in the order of one till sample per km², will suffice to define which parts of a favourable bedrock unit are most metalliferous and may even detect the tails of dispersal trains derived from small sources. Numerous examples of these regional-type dispersal trains, most discovered as part of regional till geochemical programs carried out by government agencies, are summarized in the section on Drift Prospecting. At this sampling density the large trains identified focus on areas that should be sampled at a detailed scale to clarify whether the large trains simply represent areas of high background metal levels or are com-

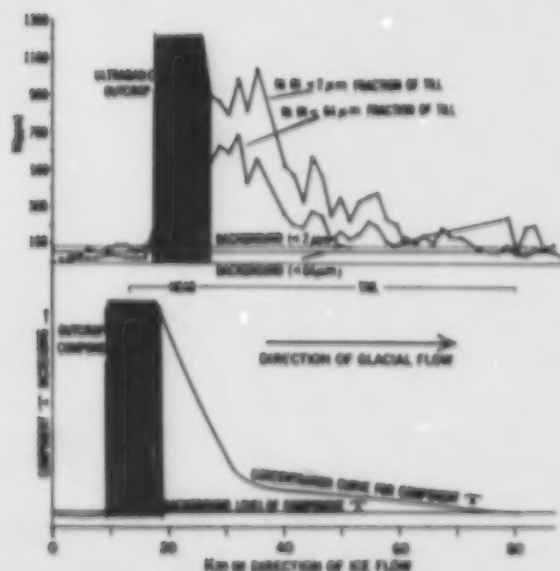


Figure 30.1. Dispersal curves for nickel in till, Thetford Mines area, Quebec. Actual (top) and idealized (bottom) curves show the relationship of the head and tail of a negative exponential curve (after Shilts 1976).

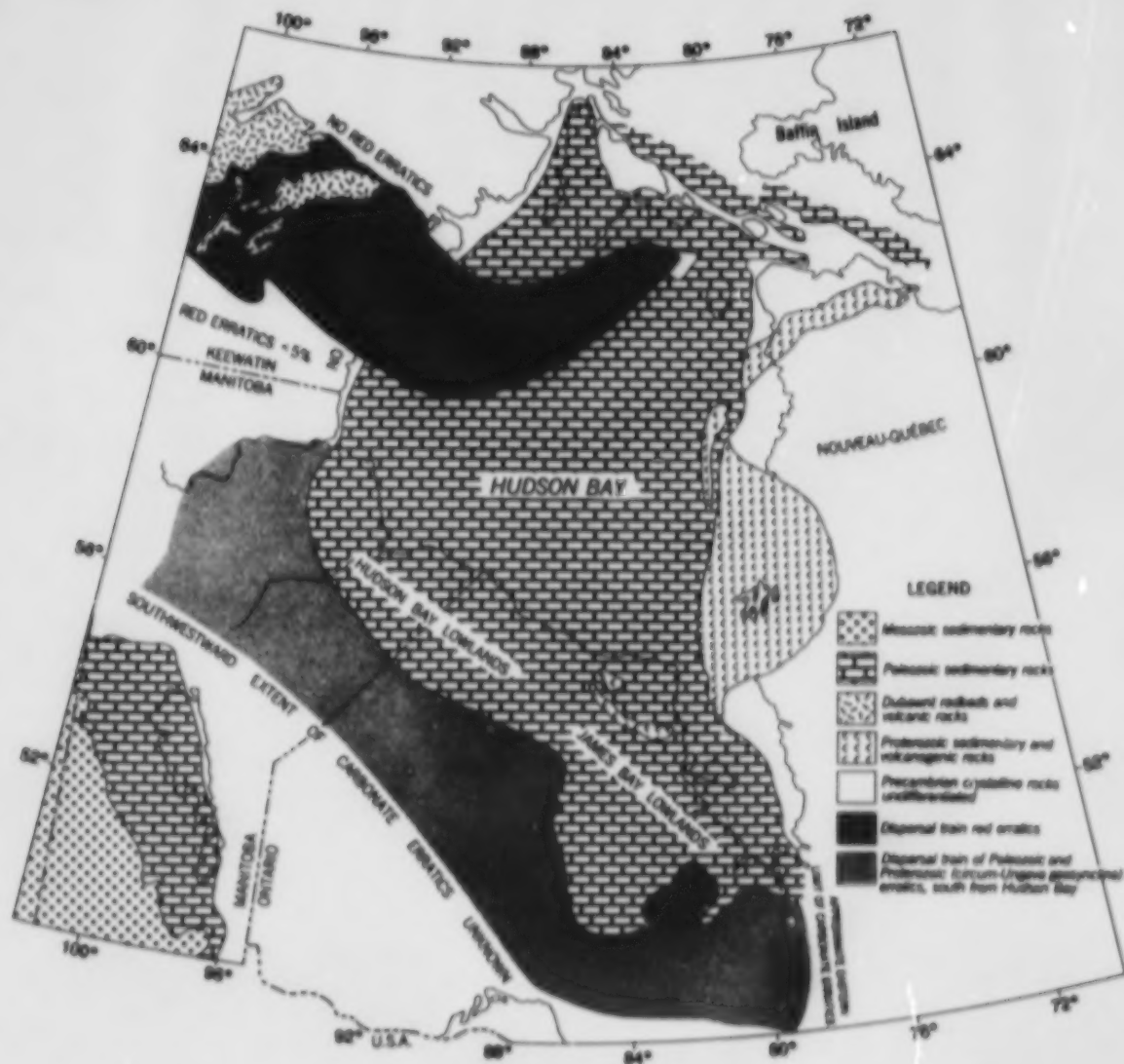


Figure 30.2. Major dispersal trains around Hudson Bay (modified from Shultz 1982b, and Kaszycki and DiLabio 1986).

posed of several overlapping small trains derived from areas of mineralized bedrock.

"Detailed" sampling, in which sample spacing is in the order of tens to hundreds of metres, is designed to locate heads of dispersal trains. This is the density of sampling that would normally be carried out in drift prospecting programs tracing trains up-ice or testing geophysical anomalies and/or favourable geological structures and/or contacts. Numerous examples of dispersal trains that have been mapped at a detailed scale are summarized in the section on Drift Prospecting. An idealized glacial dispersal model (Miller 1984) serves to illustrate (Figure 30.3) some of the characteristic features of dispersal trains: they are generally ribbon-, fan-, or flame-

shaped in outline; they have abrupt lateral contacts with the surrounding barren till, and the concentration of the distinctive component within a train decays rapidly down-ice. At this scale of sampling, postglacial mobilization of trace elements in groundwater and soil water may spread the dispersal train downslope, partially obscuring its original shape, which is the result of clastic dispersal.

Recently, increased use has been made of samples collected stratigraphically in areas of deeper overburden, using various drilling techniques to produce three dimensional data sets (i.e. Thompson 1979; Gray 1983; Averill and Zimmerman 1986; Bird and Coker 1987; Sauerbrel *et al.* 1987; Harron *et al.* 1987; Smith and Shultz 1987).

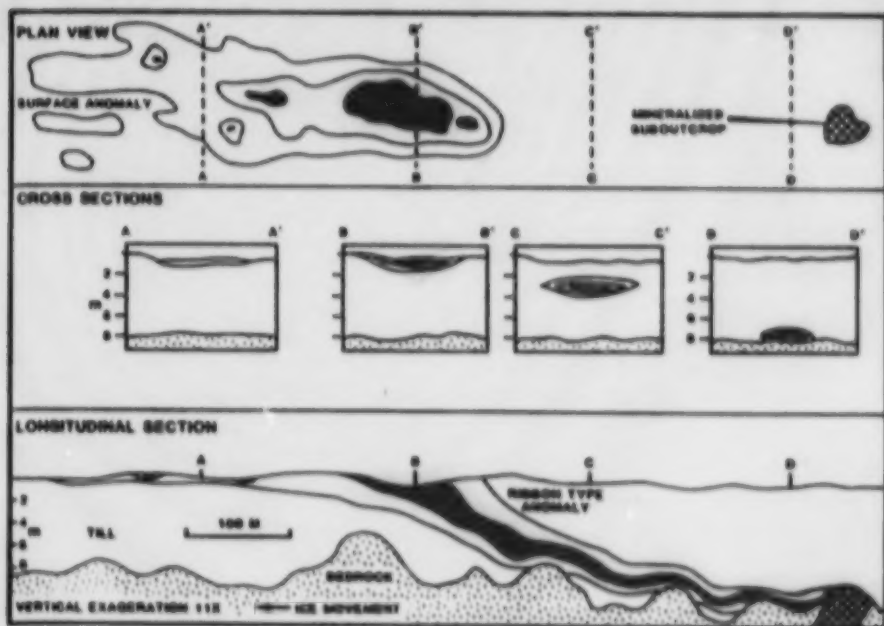


Figure 30.3. Idealized glacial dispersal model (modified from Miller 1984).

GLACIAL STRATIGRAPHY AND ICE MOVEMENT DIRECTIONS

Mineral exploration, using techniques appropriate for glaciated terrain, is still often conducted, particularly so in Canada, without attempting to understand the regional glacial history. If exploration is to succeed, it is essential to know the glacial sediment succession and which sedimentary package (i.e. which till) is related to which ice movement direction.

Till that is derived directly by erosion of bedrock is a first-cycle sediment (first derivative of bedrock of Shilts 1976) and is the optimum glacial sediment type to use for mineral exploration. Sediments resulting from the reworking of till or other unconsolidated sediments (i.e. stratified drift) are second-cycle sediments; they have been subjected to sorting and have undergone an episode of transport in water along a different path from the original. In this way, glaciofluvial gravel and sand represent the coarse fractions and glaciolacustrine silt and clay represent the fine fractions of the till(s) from which they were derived. Because these sediments have travelled along transport paths consisting of two vectors, and have been transported first by ice then by water, it is very difficult if not impossible, in thick sediment sequences, to interpret their provenance. It is far easier to trace till to its bedrock source. Till is clearly the optimum glacial sediment type to use in mineral exploration since it has the least complicated source-transport-deposition history.

Data on ice movement directions may be obtained from a variety of glacial features including: striations, crescentic marks and ice flow land forms, dispersal trains, and fabrics. Ice flow directions estimated by measurement of striae are not always the most significant flow directions in terms of drift transport (Shilts 1984b). It has been noted at several sites that the bulk of the till was deposited by movement of ice in a direction different from the ice flow direction indicated by the youngest set of striae (Veillette 1986; Kaszycki and DiLabio 1986a). Recently, there has been a movement towards 1:50 000 or 1:100 000 scale mapping of surficial geology in areas of active mineral exploration; ice-flow and provenance data at such scales can be applicable to exploration at the property scale.

The past decade has seen a substantial increase in our knowledge of glacial sedimentation, glacial dispersal patterns, glacial stratigraphy and associated ice flow directions. Several examples can be cited:

1. The Nordkalott Project, which included a regional surficial geochemistry and mapping component, was carried out by the Geological Surveys of Finland, Norway and Sweden, in these countries, north of latitude 66° (Geological Surveys of Finland, Norway and Sweden 1986a, b, c, d, e, f, and 1987). Ice movement directions were ascertained which revealed areas of simple ice flow in coastal areas and of multiple ice flows inland. Trenching and drilling, using techniques developed in major regional sampling projects carried out by the Geological Survey of Finland

- in the late 1960s and 1970s, provided data on the Quaternary stratigraphy.
2. In Labrador, Klassen and Thompson (1987) identified ice flow patterns that are simple near the coast and that become quite complex inland, reflecting the complicated ice-flow history of the central ice divide area. As a direct result, dispersal trains are ribbon-shaped near the coast and become fan-shaped and even ovoid, inland in the area of complex ice flow around the Labrador-Nouveau Québec ice divide (Figure 30.4, Klassen and Thompson, in press).
 3. In Nova Scotia, (Stea *et al.*, in press) also found, as in Labrador, that complex dispersal is recorded in areas of multiple ice flow events. Stea was able to classify different areas of Nova Scotia as to their expected sequence of ice flow events (Figure 30.5).
 4. Veillette (1986, in press) identified three ice flow events in western Québec (Figure 30.6), and showed that the intermediate one was responsible for the bulk of the drift transport. In an area of active exploration by drift prospecting, this interpretation was immediately useful in exploration. In conjunction with the work of Veillette in the Abitibi-Timiskaming area is that of Baker *et al.* (1984a, b, 1985, 1986), Baker

and Steele (1987) and Steele *et al.* (1986a, b) in the Matheson area of Ontario, and that of Bird and Coker (1987) in the Timmins area of Ontario which proposes a preliminary stratigraphic sequence with related ice flow directions for this area of Ontario and Québec (Figure 30.7) (Steele *et al.*, in press). This western part of the Abitibi greenstone belt is also explored by drift prospecting, relying on overburden drilling to sample the tills in this sequence, hence correct ice flow directions are crucial for interpretation of the data.

SAMPLING AND ANALYTICAL METHODS

The most important aspect of data collection, and the resultant sample treatment and geochemical analyses of glacial overburden, starts in the field or on the drill where it is essential to make the best possible identification of the type of glacial sediment being sampled. Appropriately educated and trained people, Quaternary geologists, or at least geologists who have had some training in Quaternary geology and/or sedimentology as well as applied geochemistry, are essential to ensure that the glacial sediments are adequately identified and logged. In Fennoscandia the use of Quaternary geologists/applied geochemists on overburden geochemical programs is ac-

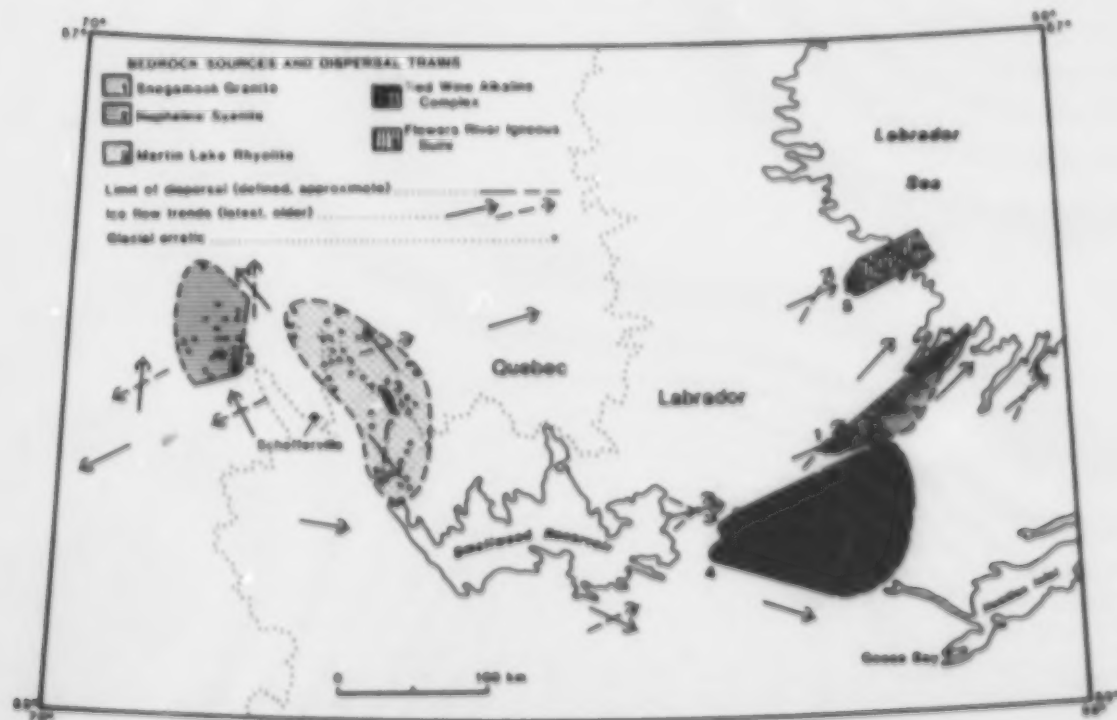


Figure 30.4. Dispersal trains in Labrador (Klassen and Thompson, in press). Broad fan shapes reflect transport in two or more phases of ice flow.

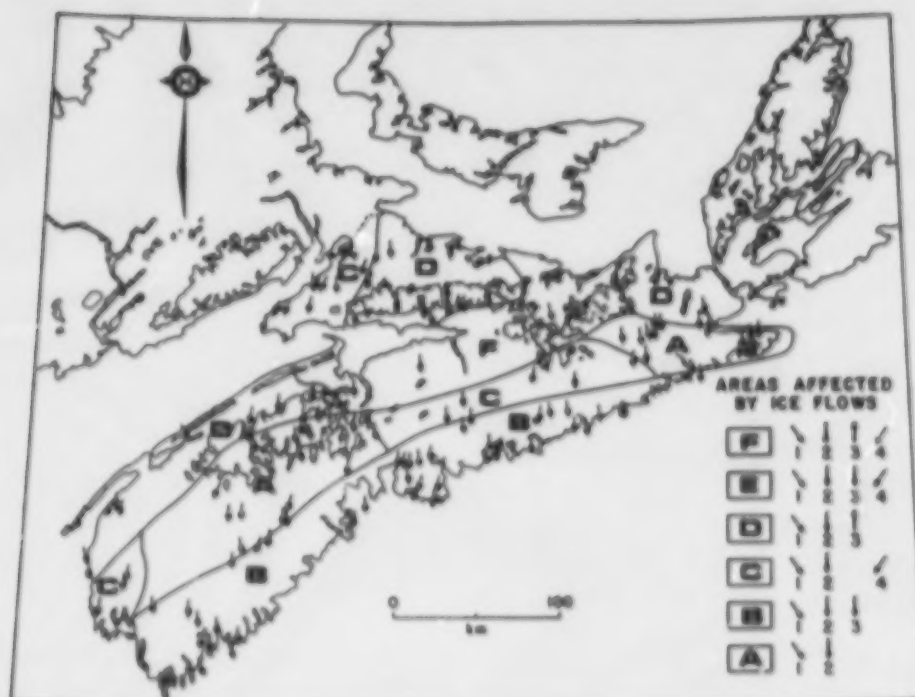


Figure 30.9. Sequences of ice flow directions recorded in Nova Scotia (Stea et al., in press).

cepted and routine. In Canada this is not the case, most overburden drilling and sampling being done by personnel trained in neither Quaternary geology nor applied geochemistry.

Correct identification of the genetic class of the glacial sediment is the key to tracing geochemically anomalous overburden back to a bedrock source. It is also essential that the stratigraphic position of the till be properly determined. In particular, it is important to determine to which sedimentary package and which ice movement direction the till belongs. It is only when identification of till and its stratigraphic position and associated ice movement direction are understood that one can confidently start tracing a pattern of geochemically anomalous till samples back to a bedrock source. Without these controls, even the most sophisticated preparation, analysis and interpretation of the data for overburden samples may be inadequate or, at best, inefficient for locating mineralization. The glacial history of an area must, in many instances, be determined as part of the overburden drilling and sampling programs.

Samples used in regional geochemical/Quaternary geology mapping programs are usually collected at or near the surface to cover a specific area, for example, a National Topographic System map sheet or favourable geological environment or structure. These samples are usually obtained from hand dug pits (<2 m) or by using small portable hand-held auger or flow-through bit type drills, or backhoes

(<5 m) (see Table 30.1). Sample collection in areas of deep overburden usually involves drilling. A number of techniques have been used for overburden drilling including augers, percussion drills, reverse circulation rotary drills (RCD) and rotasonic drills (Table 30.1). The greatest experience and success has been with reverse circulation drills, although in recent years rotasonic drills have started to play a more significant role, particularly in stratigraphic drilling programs. To date, however, no cost-effective drilling system for recovering large till samples at depths around 10 m has been devised.

In reverse circulation drilling, water, sometimes used in conjunction with compressed air, is pumped down the outer tube of the dual tube rods. The water mixes with the cuttings at the tricone bit (tungsten carbide buttons) and the slurry is forced to the surface through the inner tube. The sample slurry discharges into a cyclone, to reduce the velocity of the discharge material, and empties through a 2 mm (10 mesh) sieve into a series of sample buckets. Logging is carried out by the Quaternary geologist on the drill. The geologist sees a washed and disturbed sample which makes logging difficult for qualified personnel and just about impossible for unqualified personnel. There is only one chance to log the sample material as it goes by. In addition, the fine fraction of the material, such as the fine ore minerals including some forms of gold, is generally lost (Sheep

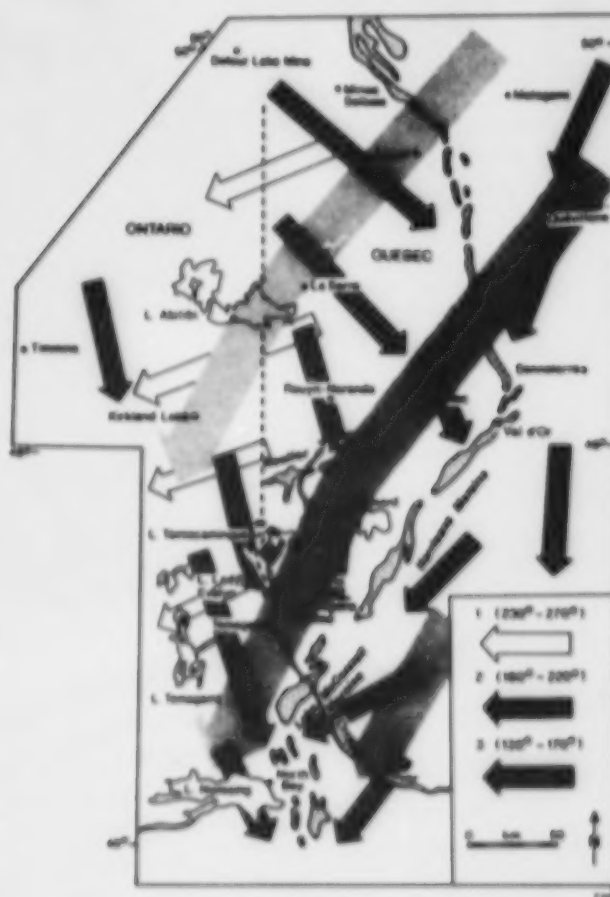


Figure 38.6. The three ice flow directions recorded in the Abitibi-Timiskaming area of Québec and Ontario (after Veilleux 1986).

and Nichol 1987), and cross-contaminated by the recirculated water.

The rotasonic drill uses high frequency (averaging 5000 rpm) resonant vibration and rotation to obtain continuous solid cores. Sediments are cored with tungsten carbide fronted bits. The cores are extruded, in 5 foot lengths, into plastic sleeves and placed into core boxes. Logging and sampling of the cores can be carried out on-site or at a later time. Rotasonic drills may produce cores that are equal in length to, longer than or shorter than the interval sampled. These variations appear to be due mainly to the manner in which different sediment types react to the drilling stresses. Also, surface deformation and internal secondary deformation due to the drilling have been observed in rotasonic drill core (Smith and Rainbird 1987).

When considering whether to use heavy mineral concentrates or a fine fraction of the till one must consider the nature and type of mineralization being sought. Routinely, heavy mineral concentrates (HMC) are prepared from the overburden drilling samples. Samples are washed through a 2 mm (10 mesh) sieve to remove all coarse material. When dealing with rotasonic core the material must first be broken up and disaggregated, which in the case of compact and desiccated tills can be difficult and time-consuming. Once the materials which are less than 2 mm in diameter are obtained they are transferred to an elevated holding tank, completely stirred by a mixer into a slurry, and released onto a sloped shaker table below. The heavier materials are separated from the lighter materials by agitation in water on the shaker table (see Sivamohan and Forsberg 1985; Stewart 1986b, on the principles of tabling). Once again, fine materials, likely including

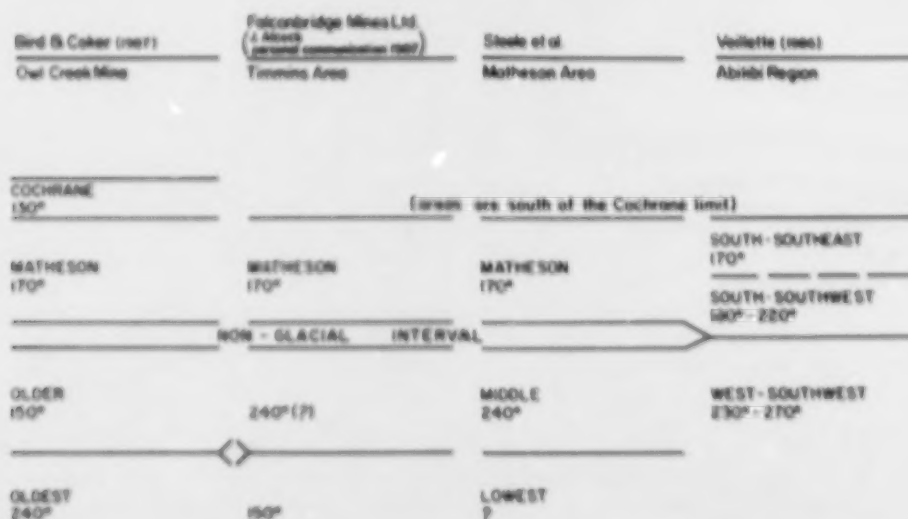


Figure 38.7. A preliminary stratigraphic sequence and related ice flow directions for the Matheson-Timmins area of Ontario (Steele et al., in press).

TABLE 38.1: FEATURES OF VARIOUS OVERBURDEN DRILLING SYSTEMS (AVERAGES BASED ON 1985 DATA).

	Reverse Circulation Drills (Longyear or Ackar) (Rodwell Mounted)	Rotasonic Drills (Rodwell or Truck Mounted)	Small Percussion and Vibrosonic Drills (Various)	Auger Drills (Various)
1. Production cost estimate per: - day (10 hrs) - metre	\$1,800 - \$2,000 \$25 - \$40	\$3,000 - \$4,000 \$50 - \$80	\$500 - \$1,000 \$20 - \$40	\$800 - \$1,500 \$25 - \$50
2. Penetration depth	Unlimited (125 m?)	Unlimited (125 m?)	10 - 20 metres (greater?)	15 to 30 metres (boulder free)
3. Environmental damage	5 metre wide trails (may have to be cut in areas of larger trees)	5 metres wide cut trails	nil	2 - 3 metre wide cut trails (Rodwell, mucking, all terrain vehicle mounted quite manoeuvrable)
4. Size of sample	5 kg (wet)	Continuous core	300 g (dry), or continuous core	3 - 6 kg (dry or wet)
5. Sample of bedrock	Yes (chips)	Yes (core)	Yes (chips) if reached	Undubly, if hollow auger, split spool sampler can be used for chips
6. Sample recovery a) till b) stratified drift	Good Moderate	Excellent Excellent	Good Good	Good Poor to moderate
7. Holes per day (10 hrs)	4 @ 15 - 20 metres 1 @ 60 - 80 metres	4 @ 15 - 20 metres 1 @ 60 - 80 metres	5 @ 6 to 10 metres	1 to 3 @ 15 to 20 metres
8. Metres per day (10 hrs)	60 - 80 metres	60 - 80 metres	30 to 50 metres	20 to 60 metres
9. Time to pull rods	10 min @ 15 metres	10 min @ 15 metres	30 to 60 min @ 15 metres	20 to 40 minutes @ 15 metres
10. Time to move	10 - 20 minutes	15 - 30 minutes	30 minutes	15 to 60 minutes
11. Negotiability	Good	Moderate	Good (poor if manually carried on wet terrain)	Good to reasonable
12. Trails required	Yes, may have to be cut in areas of larger forest	Yes, must be cut	No	Yes and no
13. Ease in collecting sample	Good	Excellent, continuous core	Sometimes difficult to extract from sampler	Good (contamination?)
14. Type of bit	Mills-tooth or tungsten carbide tricone	Tungsten carbide ring bits	Flare through sampler, continuous coring	Auger with tungsten carbide teeth
15. Type of power	Hydraulic rotary	Hydraulic-rotasonic	Hydraulic percussion (gas engine percussion, vibrosonic)	Hydraulic-rotary
16. Method of pulling rods	Hydraulic	Hydraulic	Hydraulic jack, hand jack or winch	Winch or hydraulics
17. Ability to penetrate boulders	Excellent	Excellent, cores bedrock	Poor	Poor to moderate
18. Texture of sample	Slurry (disturbed sample)	Original texture (core can be shortened, longitudinal and/or contacted)	Original texture	Original texture (dry) to slurry (wet)
19. Contamination of sample	Nil, fines (till (tungsten))	Nil (tungsten)	Nil (tungsten)	Nil to high (tungsten)

fine gold, are lost (Shelp and Nichol 1987). The tailed heavy minerals are dried and the magnetic fraction removed (using a magnet) and stored. In the case of gold mineralization associated with iron formation the usefulness of the removal of the magnetic fraction should be carefully considered. The non-magnetic fraction is further concentrated using a heavy liquid (e.g. methylene iodide, SG = 3.3) separation technique. The samples are cleaned, dried, sometimes crushed and ground and geochemically analyzed.

In the case of the rotasonic core or surface till samples the fine fraction (e.g. clay sized material (<2 μm) or -250 mesh (<63 μm)) can be separated and analyzed. In some instances, when a till has sufficient fine material to come up the reverse circulation drill in balls or lumps, it is possible to collect, in the sieve above the collection bucket, a relatively uncontaminated sample from which to obtain the fine fraction.

Heavy mineral concentrates (HMCs) and the other size fractions of tills are commonly analyzed for a wide but varied suite of elements, determined by the type of mineralization and nature of deposit being sought (see Tables 30.2, 30.3, and 30.4). All analytical work should be quality controlled using reference control and duplicate sample analysis. Analytical techniques generally include various combinations of fire assay, dissolution-atomic absorption/DCP or ICP methods. This series of analytical techniques usually involves splitting, which in the case of analysis for gold, particularly in HMCs, is problematic at best due to the nugget effect. These techniques also commonly involve destruction of the sample. Neutron activation allows non-destructive analysis of the whole sample but one must be aware of the type of irradiation used because in some cases the samples, depending on their matrices and/or chemistry, will be permanently rendered too radioactive to handle. Getting the whole HMC sample back facilitates later mineralogical work on anomalous samples to identify the nature of the mineralization, in some instances its geologic environment and in certain cases some idea of distance of transport. Contamination for elements such as tungsten and cobalt, due to fragments from tungsten carbide bits, can be detected during examination of HMCs. Caution must be exercised in utilizing the shape of gold grains, or any other mineral grain for that matter, as an indication of distance of transport, because of variability in the original shape and form of the grains and in the style of glacial transport, either over short distances in the active basal zone or over long distances in the passive englacial zone of the ice.

Exploration reliability, and success, can be increased by using properly trained personnel to log,

sample and interpret overburden data based on a framework of overburden stratigraphy and ice movement directions. The drilling method and analytical techniques employed should be considered carefully in terms of costs and the quality of data needed. The use of fine-fraction and heavy-mineral concentrate fraction geochemistry to complement each other will increase exploration reliability.

OCCURRENCE OF TRACE ELEMENTS IN TILL AND SOIL AND THE EFFECTS OF WEATHERING

In recent years, more attention has been placed on trying to understand the comminution behaviour of ore minerals, the residence sites of metals in tills and the effects of weathering on trace metal levels versus grain size (Shilts 1975). However, the amount of published information on the partitioning of metals and minerals in till is still quite small. Studies have shown that the mineralogy, petrography and major element chemistry of tills are clearly dependent on till-forming processes as well as on bedrock variations (Haldorsen 1977, 1983; Taipale *et al.* 1986).

Lithophile trace elements (Figure 30.8), tend to be enriched in the coarser grain size ranges (the size ranges of rock fragments) (DiLabio, *in press*). In this case (till derived from the Strange Lake Rare Earth Element - Nb-Zr-Y-Li-Ba deposit, Labrador) they are also enriched, to a lesser degree, in fine size ranges reflecting the fine grain size of the glacially liberated resituate and silicate minerals in which they occur in bedrock.

Chalcophile trace elements from unstable minerals such as sulphides, tend to be enriched in the finer grain size ranges as shown for copper, uranium, and arsenic (Figure 30.9) (DiLabio 1979; Shilts 1984a). The geochemically more active fraction of weathered till lies in its finer grain sizes because of the tendency of phyllosilicate minerals and secondary minerals to be enriched in the fine sizes (see DiLabio 1979; Peuraniemi 1982, 1984; Nikkarinen *et al.* 1984; Shilts 1984a). These phases have a high total surface area and cation exchange capacity, so they act as scavengers, adsorbing representative portions of trace metals released during weathering of primary, particularly sulphide, minerals. Unweathered till also shows preferential enrichment of trace metals in specific grain size ranges, and this probably reflects the grain size of primary metal-rich minerals that have been glacially comminuted (Shilts 1984a). As shown in Figure 30.9, the <2 μm fraction is the best fraction of weathered till to analyze, being the most enriched in metals. Often, however, the <63 μm (<250 mesh) fraction is analysed because of insufficient <2 μm material and because it is cheaper to recover.

TABLE 20.2: A SUMMARY OF DRIFT PROSPECTING AND RELATED OVERBURDEN STUDIES IN CANADA (1977 - 1987) (STUDY TYPE: A - REGIONAL - 1 - RECONNAISSANCE, 2 - DETAILED; B - RESEARCH - 1 - ORIENTATION, 2 - FOLLOW-UP; C - EXPLORATION CASE HISTORY. HMC - HEAVY MINERAL CONCENTRATE, RCD - REVERSE CIRCULATION DRILLING.)

Location	Mineralization	Study Type	Sample Media, Fractions and Elements	Shape and Size (L x W) of Dispersal Train	Comments	References
1. Peter (Small) and King George Lakes, N.W. Terr.	As	A-1	C-horizon till and pebble counts, <63 µm, Cu, Pb, Zn, Co, Ni, Ag, Mn, Fe, Mn, U, W and Au	N/A	Study to be published	Sparkes and Macdonald (1986)
2. Victoria and Tully Pond Areas, Nfld.	Cu, Pb, Zn	B-1	Profile sampling of B, B-C and C horizons, pebble-counter counts	N/A	Study still in progress	McCarthy (1985)
3. Buchans Area, Nfld.	Zn, Pb, Cu, Ag and Au (Buchans orebody)	A-2	B-horizon till and till, 40 mesh for bulk and HMC of till, Cu and Zn	Elbow, 8 km x 2 - 4 km	Broad zone of soils with anomalous Zn HMC, gave better anomaly contrast than 40 mesh for till	James and Perkins (1987)
4. Long Arm Area, Nfld.	Au and Cu, Pb, Zn	A-1	Till and pebbles	Dispersal in terms of 100's of metres	Study still in progress	Vanderweert and Taylor (1987)
5. Bellfleur (Map and Trapper Cove Areas), Nfld.	Zn (Trapper Prospect)	A-2	C-horizon matrix and clasts	N/A	Study still in progress	McCarthy (1986)
6. East Part of Central Mineral Belt, Labrador	U, Be, REE, Cu, Pb and Zn	A-1	Pebble count/ boulder tracing	Elbow near source (20 to 30 km) becoming further away	Study still in progress	Barnham et al. (1987)
7. East-central Labrador	U and Cu	A-1	Till: <63 µm, <63 µm and 2 - 4 mm, Cu, Pb, Zn, Co, Ni, Ag, Mn, Fe, Mn, U, W and Au	Broad ribbon to flume, from 30 to 100 km from bedrock source	Till geochemistry reflects broad variations in bedrock geology	Klassen (1983, 1984), Klassen and Smith (1984, 1985), Thompson and Klassen (1986)
8. Moran Heights, U. Labrador	U	B-1	Till and pebble counts	Elbow, 1 km x 300 m	U in till defines dispersal train	Vanderweert (1986)
9. Lettice Lake, Labrador	REE, Be and Mn	A-2	C-horizon and pebbles counted	Flume to ribbon, 600 m x 200 m	Scintillometer survey and mineralized boulders define dispersal train	Barnham and Lettice (1986)
10. Strange Lake, N. Labrador	Zr, Nb, Y, Be and REE (Strange Lake deposit)	A-2	Till from scintillometer, <63 µm, Cu, Pb, Zn, Co, Ni, Ag, Mn, Fe, Mn, U, W and Au	Elbow, up to 30 km x 5 km	Results show that Be and Pb are good indicators of the peralkaline complex	McConnell et al. (1984), Barnham et al. (1985), McConnell and Barnham (1987), Vanderweert et al. (1987)
11. Labrador Trough, Labrador	Fe, Cu, Pb, Zn, and Au	A-1	Till	Flume to flume, 60 to 70 km long	Study still in progress. Field and 97	Klassen and Thompson (1987)
12. Forest Hill, Gaspereau County, N.S.	Au (Forest Hill Gold District)	B-1	Till profiled, pebbles counted, HMC and HMC counts, <63 µm and 100 µm, Cu, Pb, Zn, Co, Ni, Ag, Mn, Fe, Mn, U, W and Au	100 to 300 m long	Gold and Au in <63 µm best for exploration. Planning for mobile Au also recommended	MacKinnon et al. (1986), MacKinnon and Sme (1986)

Continued

EXPLORATION '87 PROCEEDINGS
GEOCHEMICAL METHODS: THEIR APPLICATION TO ORE EXPLORATION

TABLE 30.2: CONTINUED.

Location	Mineralization	Study Type	Sample Media, Fractions and Elements	Shape and Size (L x W) of Dispersal Train	Comments	Reference(s)
13. Eastern Shore, Central N.S.	Au, Cu, Pb, Zn, and W	A-1	Till; <2 µm: Cu, Pb, Zn, Ni, Co, Fe, Mn, Mg, Ca, Hg, As, Mo, Ag, Cd and U.	N/A	Established regional till geochemical characteristics as a framework for mineral exploration in N.S.	Stee and Fowler (1979); Henderson and Wylie (1986)
14. Eastern Shore, Central N.S.	Au	A-1	Till and lake sediments; <2 µm - Cu, Pb, Zn, Ni, Co, Fe, Mn, Ca, Mg, Mo, Cd, Ag, As, and U; H&AC - Sn and W.	N/A	Compared geochemical relationships between tills and lake sediments. As and Pb in lake sediments and Cu and in tills were pathfinders for gold.	Rogers et al. (1984)
15. Oldham, N.S.	Au	B-2	Till, C-horizon soils; <63 µm; Au and As.	Ribbon, 2400 m x 400 m.	Both Au and As showed dispersal from known Au mineralization.	DiLabio (1982b)
16. Nova Scotia	Au, Cu, Pb, Zn, W, Sn, and U	A-1	Tills; <63 µm - Cd, Ag, Cu, Pb, Zn, Co, Ni, Fe, Mn, Ca, Mg, Mo, As, and U. H&AC - Sn and W.	Various, local tills 1 km to 4 km with exotic till (lasts from 20 to 70 km).	Baseline data on distribution and chemistry of tills in N.S. Documented dispersal from chemically distinct lithologies and mineralization of various types.	Stee and Fowler (1981); Stee and Grant (1982); Stee and O'Reilly (1982); Stee (1982a, b; 1983)
17. North Central, N.S.	Pb-Zn, Cu and U	A-1	Bedrock and till; <2 µm: Cu, Pb, Zn, Co, Ni, Fe, Mn, Ca, Mg, Mo, U and As.	N/A	Emphasized need to recognize different till sheets. Dispersal is a multistage process.	Stee et al. (1980a, b); Stee and Finch (1986)
18. Mascarene Peninsula and West Isles, N.B.		A-2	Humus, B and C-horizon; 7 and H&AC.	N/A	Study still in progress.	Cheswell (1986)
19. St. George Bathurst, Southern N.B.	W, Cu, Mo and Au	A-1	B and C-horizon (till); B-horizon - Cu, Pb, Zn, Ag, Co, Mo, U and Sn. H&AC (till) - W, Sn and Au.	Flame, 1 to 5 km long.	New possible exploration targets identified and most known mineral occurrences located.	Ramilton et al. (1986); Thomas et al. (1987)
20. Sisson Brook, N.B.	W-Cu-Mo	B-1	Till; -10 + 80, -80 + 200, -200, -10 (ground to -200 mesh and H&AC; Cu, Pb, Zn, Ni, Ag, Mo, Fe, As, F, W, Sn and Bi.	Ribbon to Flame, 200 to 400 m x 700 m.	Short dispersal on property due to bedrock ridge. Anomalous till carried over ridge and deposited 8 km down-ice with no connecting dispersal train.	Snow and Coker (1987)
21. West Central N.B.	Cu, Pb, Zn, Sn, W and Mo (Maramba Zone)	A-1	Till; <2 µm: Cr, Mn, Fe, Co, Ni, Cu, Zn, Mo, Ag, Cd, Pb, W, As, U, Sn and F.	Several km in the direction of ice flow.	Till down-ice from known mineralization shows dispersal. New unexplained anomalous exist. Study still in progress.	Lamothé (1986)

Continued

TABLE 39.2: CONTINUED.

Location	Mineralization	Study Type	Sample Media, Fractions and Elements	Shape and Size (L x W) of Dispersal Train	Comments	Reference(s)
22. Trousen Lake Area, N.B.	Zn, Pb, Cu and Ag	A-2	B and C-horizon (till): -40 mesh; Cu, Pb, Zn, Mn, Fe, Ag, Co, Ni, Mo, U and Au.	Local, 1 to 2 km long.	Anomalous patterns related to known mineralization or distinct bedrock lithologies.	Fyffe and Prank (1983)
23. Tetagouche L. and Upsalquitch Forks Map Areas, N.B.	Cu, Pb, Zn and Au	A-2	B and C-horizon (till): -40 and -250 mesh; Cu, Pb, Zn, Ag, Mn, Fe, Ni, Co, Cd, Mo, As, Sb and Au.	N/A	Outlined presence of known Au mineralization and targets for further exploration.	Prank (1985, 1986a, b, 1987)
34. Central Gaspé Peninsula, Quebec	Cu, Mo, Pb and Zn	A-2	Back-hoe pits profile sampled (till): <2 µm and H&C.	Two trains of granitic erratics - one is 110 km x 70 to 50 km and the other is 40 km x 20 km.	Recognized dispersal from two distinct glacial events.	David and Bedard (1988); Chaurin and David (1987)
25. Southwest Gaspé Peninsula, Quebec	Au, Cu, Pb and Zn	A-1	C-horizon (till): -40 (ground to -200) mesh; Au, trace and major elements; -40 + 250 mesh H&C; Au + 25 elements and examined for mineralogy and Au grains.	N/A	Au analysis of H&C's provided a good estimate of Au variation across area and outlined a number of anomalies.	Bernier et al. (1987)
26. Northwest Gaspé Peninsula, Quebec	Au, Cu, Pb and Zn	A-1	Till - pebble counts.	N/A	Pebble counts indicate a complex ice flow history for the area. Study still in progress.	Pichonnet and Desmarais (1985)
27. Lac Magantic Area, Quebec	Au, Mo, Cu, Pb, Zn, W	A-1	Till, pebble and boulder counts, fabrics; <64 µm; Al, Fe, Mn, Ca, Mn, Ba, Co, Sr, Ti, Zr, Cu, Ni, Cr and V. Mineralogy of various fractions studied.	Ribbon to Rama, 80 km x 15 km.	Detailed study of the Quaternary history and sediments of the area, including glacial dispersal from Thorford Mines ultrabasic outcrops.	Shultz (1975a, 1975 and 1981)
28. Eastern Townships, Quebec	Au	A-1	Variable cut land stream sediments or other sediment types; H&C; Au; Fe, Mn, Cu, Zn, Ag, Pb, Cr, Co, Sb, La, ni, S, As, Ti, Mo, Sn, V, Ta, W, Th, U.	Flame, 20 to 30 km x 15 to 20 km.	Widespread anomaly patterns related to glacial rather than alluvial processes for H&C from streams.	Maurice and Mercier (1983); Maurice (1986a, b)
29. Beauportville, Quebec	Au (placer)	B-1	Till and other sediments; <2 µm; Ni.	N/A	Reconnaissance drilling program confirmed presence of these tills and associated sediments from at least three glacial events. Characteristics of Au placer-bearing strata outlined. Study still in progress.	Shultz and Smith (1986a, b); Smith and Shultz (1987)

Continued

EXPLORATION '87 PROCEEDINGS
GEOCHEMICAL METHODS: THEIR APPLICATION TO ORE EXPLORATION

TABLE 38.2: CONTINUED.

Location	Mineralization	Study Type	Sample Media, Fractions and Elements	Shape and Size (L x W) of Dispersal Train	Comments	Reference(s)
30. Lac Mistassini - Lac Waconichi Area, Quebec	Cu (Iron Mine)	A-2	D-horizon, <80 mesh Cu; Till - pebble counts.	Ribbon to flama, Two trains 1650 m x 75 m and 600 m x 300 m	Thorough documentation of a glacial dispersal train. Mapping abundance of mineralized pebbles most efficient guide to ore zones.	Ouellet (1981)
31. Ungava, Quebec	Ni, Pt, Pd	A-1	Till, <63 μ m - CaCO ₃ and multielement geochemistry. Rock - mineralogy, granulite lithology counts.	Several dispersal trains ranging from 6 to 10 km up to 70 km in length.	Documents the glacial history including ice flow patterns of the Ungava Peninsula. Geochemistry of the till is still under study.	Bouchard and Marcotte (1986)
32. Case-Berard Area, Quebec	Au (Golden Pond and Golden Pond East)	C	Till, sand and gravel from MCD holes; H&AC, Au, As, and S, also carried out gold grain counts.	400 m x 200 m, but truncated against a bedrock ridge by later glacial advance and erosion.	Successful application of H&AC, in a new gold camp.	Sauerbrey et al. (1987)
33. West Central Quebec	Au, Cu, Pb and Zn	A-1	Till, <80 mesh and H&AC; Cu, Zn, Pb, Ni, Co, Mn, Ag, Bi, Sr, Mo, Sb and V.	60m	Provided regional data on till geochemistry.	Lafleche and Lafleche (1983); Lafleche et al. (1983a, b)
34. Bouvet Area, Malartic, Quebec	Au (Dayton Mine and Bouvet Mine)	B-1	Humus, Till - 100 mesh and H&AC; Au, Cu, Pb, Zn and Ag.	Dayton Mine - 700 m long; Bouvet Mine - 15 to 30 m long.	Shows the influence of bedrock topography on size and shape of dispersal train in till. Au content of -100 mesh and H&AC fractions of till both define trains. Humus can be reflective in areas covered by glaciolacustrine clays.	Gleeson and Sheehan (1987)
35. Hesperiden, Ontario	Zn	B-1	C-horizon (till), <2 μ m; Zn, Cd and Ag. Also mapped mineralized boulders and analyzed plants.	Ribbon, 400 m x 70 to 200 m.	Dispersal train best defined by mineralized boulders and Zn and Cd in till. Plant metal levels reflect those in underlying till.	Ouellet et al. (1982); Sinclair (1986)
36. Lanark County, East Ontario	Au	B-1	Humus, B-horizon soil and till (total -250 mesh and H&AC; Au. Pebble counts and mineralogy of H&AC's determined.	Irregular flama, 100 to 3000 m x variable widths.	Au in all media reflected mineralization. Au in H&AC's gave best anomaly definition and contrast. The -250 mesh fraction was most cost effective.	Gleeson et al. (1984); Remington et al. (1986)

Continued

TABLE 26.2: CONTINUED.

Location	Mineralization	Study Type	Sample Media, Fractions and Elements	Shape and Size (L x W) of Dispersal Train	Comments	References
37. Matachewan, N.E. Ontario	Barite	B-1	Till, pebbles (boulders and round) has examined barite content of 1 size fractions of till determined. Excavated trench sampled.	20 m x 50 m.	Variation of barite with distance from vein obays negative exponential function in all fractions except fine sand. Very short dispersal due to bedrock topographic effects.	Stewart (1986a)
38. Matachewan, N.E. Ontario	Au	B-1	Backhoe and auger sampling of till, < 63 µm and HMC, Au and Ag.	Ribbon to irregular shape, 100 m to 800 m x 60 to 150 m.	Outlined at least three dispersal trains.	Stewart and Van Hees (1982)
39. Kirkland Lake Area, Ontario (KLA)	Au and Cu, Pb and Zn	A-1	RCD and backhoe sampling of tills and related sediments, < 63 µm and HMC, Cu, Pb, Zn, Ni, Mn, As, Ag, Au and U. Collected and analyzed bedrock chips.	N/A	Provided baseline data for a regional Quaternary stratigraphic framework. Also provided geochemical and mineralogical data on tills in the area.	Thomson and Gunder (1979); Thomson and Wadsworth (1980, 1981); Averill and Thomson (1981); Thomson and Laurim (1981); Laurim and Thomson (1981); Routledge et al. (1981); Laurim (1982a, b); Fortescue and Laurim (1982); Averill and Fortescue (1983); Fortescue et al. (1984)
40. Kirkland Lake Area, Ontario	Au	B-2	Tills (-250 mesh) and humus (-50 mesh). Au, blasted bedrock and surficial sediments collected and analyzed rocks for Au.	N/A	Used available surficial sample media to cost effectively follow-up RCD data and outline viable gold targets for future exploration.	Gleeson and Sampson (1987)
41. Matheson - Lake Abitibi Area, NE Ontario (SMA)	Au, Cu, Pb and Zn	A-1	Rotasonic drill and backhoe used to obtain till and other sediments, HMC, -30 and -10 mesh fractions, variably analyzed for a suite of some 45 trace and major elements.	N/A	Provided baseline data on the regional Quaternary stratigraphic sequence and on the geochemical character of tills and other sediments in the area.	Baker et al. (1984a, b; 1985; 1986); Jensen et al. (1985); Steele et al. (1986a, b); Averill et al. (1986); Jensen and Baker (1986); Ontario Geological Survey (1986a, b, c; 1987); Baker and Steele (1987); Blouin (1987)
42. Macklem Township, NE Ontario (Saguenay)	Au (Aqueous Deposition)	C	RCD continuous sampling of surficial sediments (till, -10 mesh HMC, Au and Ag grain counts).	Ribbon to narrow fan, > 1 km in length.	One of the first case histories documenting the successful use of RCD data in the discovery of a Au deposit.	Gray (1983)

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EXPLORATION '87 PROCEEDINGS
GEOCHEMICAL METHODS: THEIR APPLICATION TO ORE EXPLORATION

TABLE 39.2: CONTINUED.

Location	Mineralization	Study Type	Sample Media, Fractions and Elements	Shape and Size (L x W) of Dispersal Train	Comments	Reference(s)
43. Currie - Bosman Township, NE Ontario	Cu (Currie - Bosman Deposit)	C	RCD sampling of till, -10 mesh H&C; Cu, Pb, Zn, Ag and Au.	Ribbon to narrow fan 1000 + m x 500 m.	One of the first published works on the successful use of RCD in mineral exploration in an area of thick overburden. Resulted in the discovery of the Currie - Bosman Cu deposit.	Thompson (1979)
44. Hayle Township, 18 km NE of Timmins, Ontario	Au	C	RCD sampling of glacial sediments, -10 mesh H&C; Au, Cu, Zn and As.	Ribbon, 1.5 to 2.0 km x 500 m.	Defined anomalous area, but dispersal limited due to a bedrock ridge.	Harris et al. (1987)
45. Hayle Township, 18 km NE of Timmins, Ontario	Au (Owl Creek Gold Mine)	B-1	RCD and snit sampling of glacial sediments, -10 mesh H&C; Au. Pebble lithologies determined.	Two dispersal trains at different stratigraphic levels. Ribbon, 450 m x 200 m and 650 m x 200 m.	Dispersal controlled by bedrock topography. Established Quaternary stratigraphy and ice movement directions.	Bird and Coker (1987)
46. Hemlo Area, North Central Ontario	Au	A-2	Surficial mapping to outline the Quaternary stratigraphy and terrain types.	N/A	Stresses importance of understanding the Quaternary stratigraphy in terms of composition and thickness for selection of sample media for Au exploration.	Geddes and Kristjansson (1988)
47. Hemlo Area, Hemlo Township, North Central Ontario	Au (Williams Property)	B-1	Percussion drill and flow through sampler; Humus, B-horizon soil and till; humus, various fractions of soil and till (including H&C) analysed for Au, Cu, Pb, Zn, Ag, Fe, Mn, Mo, Bi, Ba, As and W.	Irregular oval, 200 m x 250 to 500 m (limited down-ice dispersal due to bedrock topography).	Varied, but similar response in all sample media, controlled by bedrock topography, overburden thickness and the presence/absence of calcareous till.	Gleeson and Sheehan (1987)
48. Beardmore - Geraldton Area, NW Ontario	Au (Northern Empire, Enns Lake and Archie Lake areas)	B-1	B-horizon soil (-40 mesh) and till (-250 mesh and H&C); Ag, As, Cu, Cr, Zn, Pb, Sn, Bi and Au.	N/A	Orientation study that Au, in all fractions, was the best indicator of the Au mineralization.	Cross and Sade (1976)
49. Onaman River, 80 km N of Beardmore, Ontario	Au (Tacheta-Nipigon Gold Mine)	B-1	Till (C-horizon soil): <2 µm for Cu, Zn, Ag, Bi, Ba, Co, Mn, Fe and As; <63 µm for Au and carbonate content. 1000 examination of selected H&C.	Fans, 600 m x 100 to 200 m.	Au gave restricted anomalies whereas the minor, -10 mesh boulders and Cu, Ag and Fe defined the dispersal train.	Dillabio (1982a)

Continued

TABLE 39.2: CONTINUED.

Location	Mineralization	Study Type	Sample Media, Fractions and Elements	Shape and Size (L x W) of Dispersal Train	Comments	Reference(s)
50. Burton Mine Area, Leef Rapids, Manitoba	Cu-Zn (Burton Mine), Au	B-1	Till; <2 µm for Au and HbC; for Au and Au. Gold grains counted.	Irregular oval to fan, up to 1 km long	As in <2 µm and Au in HbC; defining dispersal from fault zone.	Nielsen (1986a)
51. NW Manitoba (1:250 K map sheets 64C and F)	Various	A-1	Till (2 - 3 per 100 km); <2 µm: Cu, Pb, Zn, Ni, Cr, Mn, Fe, Mn and Au	Irregular oval to fan, up to 25 km long	Trace element contents of till reflect large scale chemical variations in bedrock and mineralization. Carbonate content of the tills related to provenance.	Koznyk and Orsho (1986a, b)
52. Lynn Lake, Manitoba	Au (Agassiz Deposit)	A-1/2	Till; <2 µm and HbC; Cu, Pb, Zn, Ni, Cr, Mn, Fe, Mn, U, Hg, Ag, Au, As, W and Sb	Fan to fan, 150 m to 400 m long	Dispersal defined by Cu, Pb, Zn, Ni, As and Au in <2 µm and by Au in HbC.	Nielsen (1982, 1983); Fedakow (1983, 1984); Fedakow et al. (1984)
53. Farley Lake, Manitoba, 40 km E of Lynn Lake	Au (Agassiz Metasect)	A-2	Till; <2 µm and HbC; Cu, Pb, Ni, Zn, Cr, Cr, Fe, Mn, As, and Au.	Very local dispersal.	Till in area mainly derived from bedrock to the north of the greenstone belt. HbC's indicate gold mineralization; <2 µm fraction does not.	Nielsen and Graham (1984, 1985)
54. Minton Lake - Nickel Lake Area, E of Lynn Lake, Manitoba	Au (Agassiz Metasect)	B-1	Till; <2 µm and HbC; Cu, Pb, Zn, Ni, Cr, Cr, Fe, Mn, As and Au. Gold grain counts.	Dust Lake - 1.5 km long; Agassiz Deposit 150 m long.	Mineralization shown by As in <2 µm fraction and Au in HbC's. Length of dispersal related to local topographic controls.	Nielsen (1985, 1986a); Nielsen et al. (1985); Nielsen and Fedakow (1986)
55. Seal River Area, E of Great Island, Manitoba	Au	B-2	Till; <2 µm, <63 µm and HbC; various of Cu, Pb, Zn, Ni, Cr, Cr, Fe, Mn, As, Sb and Au. Textural analysis and palaeolithology.	Alleen to fan, 1.5 km x 0.5 km.	As in <2 µm and Au in <63 µm gave highest values and contrast. Au and As in <63 µm poor short and narrow dispersal.	Dredge and Nielsen (1980); Nielsen (1986b, 1987)
56. Northern Manitoba	Various	A-1	Till; <2 µm: Cu, Pb, Zn, Cr, Ni, Cr, Mn, Fe, As and U.	0 to 5 km in the west, greater in the east.	Anomalies in sandy till indicate local bedrock source; these in silty till are unrelated to underlying bedrock.	Dredge (1985a, b)
57. Northwestern Manitoba	Various	B-1	Till and silt; <2 µm: Cu, Pb, Zn, Cr, Ni and Ag.	0 to 5 km from source.	Till geochemistry reflects bedrock underlying or directly up-ice from till sample.	Dredge (1981)

Cont. and

EXPLORATION '87 PROCEEDINGS
GEOCHEMICAL METHODS: THEIR APPLICATION TO ORE EXPLORATION

TABLE 30.2: CONTINUED.

Location	Mineralization	Study Type	Sample Media, Fractures and Elements	Shape and Size (L x W) of Dispersal Train	Comments	Reference(s)
58. Duddridge Lake, 60 km NW of Lethbridge, Saskatchewan	U (Duddridge Lake Prospect)	B-1	Used percussion drill with flow through bit to collect till - J30 mesh and H&C (-40 + 230 mesh); Cu, Zn, Co, Pb, Ag, Mn, Al, Fe, Mn and U.	Ribbon to narrow fan, 3 km x 60 to 400 m.	Both the 230 mesh material and H&C depicted anomalous dispersal patterns in U, As and Co.	Lawson and Lefebvre (1979)
59. Waddy Lake, 140 km NW of Lethbridge, Saskatchewan	Au (EP Zone at Waddy Lake)	C	Soil drill used to collect till, H&C, Au, Pb, Ag, and Zn. Gold grain counts done.	Classic ribbon to narrow fan, 600 m x 50 to 100 m.	Successful use of H&C and grain counts to discover a new gold deposit.	Averill and Zimmerman (1986)
60. Waddy Lake No. 1 of Lethbridge, Saskatchewan	Au (Star Lake Deposit) and Waddy Lake Prospect	B-1	Till, <2 µm, -40 mesh and H&C; Au. Gold grain counts, size fractionation and analysis of the fractions for selected till.	Ribbon to oval, Star Lake - 300 m x 75 to 100 m. Waddy Lake - 600 m x 150 m.	Gold grain counts and Au in till defining large distinct dispersal patterns. Au in the <2 µm and -40 mesh give only restricted patterns near mineralization. Fractionation data indicate most gold is in the <2 µm fraction.	Lawson et al. (1986)
61. Waddy Lake Area, NW of Lethbridge, Saskatchewan	Au (several Au deposits in the area)	A-2	Till, <0.1 mm and H&C; Au, Cu and As. Gold grain counts, pebble counts and textural analysis performed on the samples.	spk	Bulk till from C horizon is an effective sample medium. H&Cs and <0.1 mm fractions contained anomalous Au. The Au is mainly fine grained.	Campbell (1986)
62. Sulphide - Holden Lake Area, 30 km NW of Lethbridge, Saskatchewan	Au (a number of sulphide-hosted Au deposits occur in the area)	A-2	Till, <0.1 mm and H&C; Au, Pb, Mn, Co, Cu, Zn and Ag. Gold grain counts and textural analysis performed on the till.	spk	Au was the best indicator of mineralization. Both H&Cs and fine fraction should be analyzed for Au in exploration.	Campbell (1987)
63. Viven Lake, Athabasca Basin, N Saskatchewan	U - M (Cotton Bay 'B' Zone)	C	RCD used to sample till; H&C, U, Co, Pb, Mn and As.	Isolated oval block of anomalous till.	A block of anomalous till was transported ~1.5 km and deposited isolated from its source.	Geddes (1982)
64. Mophon Lake, Athabasca Basin, N Saskatchewan	U (Mophon U Deposit)	B-1	Percussion drill with flow through bit used to collect till - J30 mesh and H&C (-40 + 230 mesh); Cu, Zn, Co, Pb, Ag, Mn, Al, Fe, Mn and U.	Ribbon, 3 km x 100 m.	The mineralization was best depicted by U in the <2 µm material.	Lawson and Lefebvre (1982)

Continued

TABLE 30.3: CONTINUED.

Location	Mineralization	Study Type	Sample Media, Fractions and Elements	Shape and Size (L x W) of Dispersal Train	Comments	Reference(s)
65. Athabasca Basin, N Saskatchewan	U (several U deposits occur in the area)	A-1	Boulder tracing program.	Ribbon to fan, from 3 km to 25 km long.	Used the distribution of glacial erratics to locate fracture zones and mineralization.	Ramackers et al. (1982)
66. Chuff Lake Carwell Structure, N Saskatchewan	U (Claude Orebody)	C	Percussion drilling used to sample till; 40 mesh; Ag, As, Au, B, Cu, Mn, Ni, Pb, Se, Ti, U, V and Zn.	Ribbon 1.5 to 2.0 km x 250 m.	Successful use of till geochemistry in locating U mineralization.	Wilson (1980)
67. S. of Baker Lake, District of Keewatin, N.W.T.	U-Cu, Ni-Cu and Cu-Zn (Kanan Falls, Ferguson Lake, and Hering Lake)	B-1	Till from mudbanks, plants; <2 µm and, from selected samples <63 µm and sand-size fractions; Cu, Pb, Zn, Co, Bi, U, Ag, Mo, Cd, Cr, Mn and Fe.	Fan to fan, >100 m x 150 m (three dispersal trains)	The zones of mineralization are best outlined by trace elements in the <2 µm fraction of the till. Plant metal levels reflect those in till.	Dilabio (1979), Dilabio and Rance (1980)
68. Bathurst Horseshoe, 90 km SSW of Bathurst Inlet, N.W.T.	Zn, Pb and Cu (Bathurst Horseshoe)	B-1	Soil profile (concrete layer and at 0 - 25 cm and 25 - 64 cm); 40 mesh; Ag, Ca, Cd, Cu, Fe, Mn, Pb and Zn.	Ribbon to fan, >400 m x 100 to 400 m.	In zone of weathering all sulphides destroyed. Ag, Fe and Pb show well developed dispersal patterns Cu and Zn have undergone hydromorphic dispersion.	Miller (1979), Miller (1980)
69. Aberdeen Lake, 125 km W of Baker Lake, District of Keewatin, N.W.T.	U	B-1	Soil (till?) from mudbanks; U, Mo, Cu, Pb, Zn, Ni, Co and Ag.	Ribbon to fan, 1 to 2 km x 100 to 400 m.	Successful use of multi-variate statistics to interpret a large till geochemistry database.	Rice et al. (1980)
70. Buttle Valley, Vancouver Island, B.C.	Cu, Zn, Pb, Au and Ag (Lynn, H.W., Eliza and Price Mines)	A-2	Till; <2 µm; Cu, Zn and Pb. Qeol. lithology counts, textural analysis of selected tills and tillat mineralogy.	Confined to along valleys, <20 km long.	The <2 µm fraction was anomalous in Cu, Zn and Pb over a distance of 20 km. Dispersal controlled by and confined to valleys.	Hosack (1986)
71. St. Elias Mountains, Northwestern B.C.	Cu, Co, Zn, Pb, Ag (Windy-Craggy)	B-1	Glacial erratics (mineralized clasts); pulverized; Cu, Zn, Pb, Ni, Co, Mn, Ag, Mn and P.	N/A	Compared chemistry of mineralized erratics to ore from Windy-Craggy. Statistical analyses showed that mineralized erratics were not from Windy-Craggy and likely came from another source.	Gray et al. (1987)

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TABLE 38.3: A SUMMARY OF DRIFT PROSPECTING AND RELATED OVERBURDEN STUDIES IN FINNOSCANDIA (1977 - 1987) (STUDY TYPE: A - REGIONAL, 1 - RECONNAISSANCE, 2 - DETAILED; B - RESEARCH - 1 - ORIENTATION, 2 - FOLLOW-UP; C - EXPLORATION CASE HISTORY. HMC - HEAVY MINERAL CONCENTRATE, RCD - REVERSE CIRCULATION DRILLING.)

Location	Mineralization	Study Type	Sample Media, Fractions and Elements	Shape and Size (E x W) of Dispersal Train	Comments	Reference(s)
1. Ahvenisto, S.E. Finland	Sn	A-2	Till - preconcentrated in the field and HMC, < 63 μ m; Hmuc; variously analysed for wide range of elements, lithology of till, studied.	Plasma, 8 km x 3 km.	HMCs anomalous in Sn, are effective for reconnaissance exploration. The < 63 μ m fraction gave anomalies in Sn and Cu, was more effective for detailed work. Program discovered Sn mineralization. Microbiological work classified different types of carbonate related to different deposit types.	Miettinen and Poutanen (1980); Poutanen et al. (1984); Poutanen and Rautanen (1985); Poutanen (1987)
2. Yhtymä, S.W. Finland	Cu and W	B-1	Till, 250 - 50 μ m fraction counted for mineralogy; 225 - 50 μ m analysed for Cu.	Plasma, > 2 km x 800 m.	Defined down-up maxima for dispersal of different ore and gangue minerals and related their positions to their mechanical stability.	Kinnunen (1979)
3. Kortesjärvi, S.W. Finland	Pb	B-1	Till, profile sampled to bedrock, < 60 μ m. Multielement analysis.	< 150 m long.	Searching for more ore in an area containing abundant ore boulders. Dispersal is short and from several small sources.	Spärkfeldt (1977)
4. Kaitanen, W. Finland	W	B-1	Till, 250 - 63 μ m HMC, counted for scheelite; < 63 μ m analysed for W.	Alkion to Ranta, 2 km x 250 m.	Developed scheelite - tracing method which led to the discovery of mineralization.	Isaksson and Spärkfeldt (1976)
5. Suominen, W. Finland	Mn, Cu and Au	B-1	Till, < 60 μ m; Cu and Mn. Also collected and analysed bedrock and stream sediments.	Spk.	Mn and Cu in the till anomalous over much of the granite batholith and reflected underlying bedrock because dispersal was short. Litho-geochemistry recommended if samples can be obtained cheaply.	Nurmi and Isaksson (1984)

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TABLE 36.2: CONTINUED.

Location	Mineralization	Study Type	Transport Mechanisms	Shape and Size of Dispersed Train	Comments	References
6. Redwood, South Central Finland	Zn, Cu and Ni	A-1	Transport of Zn, Cu and Ni from a source area to a distance of 100 m. The transport is associated with the presence of a dispersed train of glacial till.	Dispersed train of glacial till, 100 m long, 10 m wide, 1 m high.	Successful use of all geochemistry in the evaluation of mineralization.	Dilabio (1982)
7. Turku, South Central Finland	Ni, Cu	B-1	Transport of Ni and Cu from a source area to a distance of 100 m. The transport is associated with the presence of a dispersed train of glacial till.	Dispersed train of glacial till, 100 m long, 10 m wide, 1 m high.	Crystalline material, three-dimensional structure of a dispersed train.	Murto (1976)
8. North Karelia, S.E. Finland	Cu, Pb, Zn and Ni (Chyokumpu Area)	A-2	Transport of Cu, Pb, Zn and Ni from a source area to a distance of 100 m. The transport is associated with the presence of a dispersed train of glacial till.	Dispersed train of glacial till, 100 m long, 10 m wide, 1 m high.	Several curves of down-ice distribution of indicator elements and trace element data give the range of expected dispersed distances for the area.	Selkälampi and Hietanen (1982), Selkälampi and Hietanen (1983)
9. Oulainen, North Karelia, S.E. Finland	Cu, Pb, Zn and Ni (Chyokumpu Area)	A-1	Transport of Cu, Pb, Zn and Ni from a source area to a distance of 100 m. The transport is associated with the presence of a dispersed train of glacial till.	Dispersed train of glacial till, 100 m long, 10 m wide, 1 m high.	In an area of two ice flows, dispersal of boundaries and irregularity, as indicated by mineral of the Chyokumpu association, were from the same source.	Aarnio and Selkälampi (1983)
10. North Karelia, S.E. Finland	U	A-2	Transport of U from a source area to a distance of 100 m. The transport is associated with the presence of a dispersed train of glacial till.	Dispersed train of glacial till, 100 m long, 10 m wide, 1 m high.	U leached out of the top 1 m of till in well drained areas. Anomalous in dispersed till, classified as "anomalous" in the literature, classified in discovery of U mineralization.	Spittkötter (1976)
11. Kihniöjärvi, North Karelia	Cu	A-1	Transport of Cu from a source area to a distance of 100 m. The transport is associated with the presence of a dispersed train of glacial till.	Dispersed train of glacial till, 100 m long, 10 m wide, 1 m high.	Data on Cu content of till dispersed into indicator elements on the basis of indicator elements from mineral sample made.	Selkälampi (1982)

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EXPLORATION '87 PROCEEDINGS
GEOCHEMICAL METHODS: THEIR APPLICATION TO ORE EXPLORATION

TABLE 34.3: CONTINUED.

Location	Mineralization	Study Type	Sample Media, Fractions and Dimensions	Shape and Size (L x W) of Dispersal Train	Comments	Reference(s)
13. Suomenniemi, S.E. Finland	Au, Mo and W	A-2	Till: <63 µm, Cu, Co, Mn, Fe, Pb and Zn and later analysed for Au, Mo, W and Au.	Subsides, 12 km x 2 km (defined by Mo data)	Au, Mo and W patterns in till differed; each related to a different source. Steeply increase in sampling density in follow-up of reconnaissance data. Uncovered mineralization.	Leiminen and Martikainen (1965, 1966)
13. Eufonia Central Finland	Mo	A-1	Till: <63 µm, Mo, Cu, Mn, Fe, Pb and Zn.	Mo	Normative composition of the fine fraction of till reflects broad provenance areas, useful in identifying different till.	Tienala et al. (1986)
14. Eufonia Central Finland	Mo, Cu, Zn and Pb	A-1	Till: <63 µm, Cu, Co, Cr, Mn, Fe, Pb, Zn and Fe	Mo	Evaluated hydromorphism on the geochemistry of till. Detected original clastic geochemistry despite hydromorphism. Factor analysis classified till samples into geochemically recognizable groups.	Puranen (1982)
15. Eufonia Central Finland	Mo, Cu, Zn and Pb	A-1	Till: <63 µm - Cu, Co, Cr, Mn, Fe, Pb, Zn and Fe. 1:64-4:100 - Fe (Chondritic)	Mo	Measured metal contents of the fine fraction of the till lower than expected based on amount of gold in matrix, although their ratio is strong.	Leiminen and Tienala (1985)
16. Harjavalta, Lapland, N.E. Finland	Mo	B-1	Bedrock and till in fractions were measured for magnetic susceptibility. Antiferromagnetic till was compared to conventional grain fabric.	Dispersal on the order of 2 km long	Established magnetic susceptibility (magnetite content) as a measure of clastic dispersal.	Puranen (1977)
17. Lapland, N. Finland	Mo	A-1	Regional study of Quaternary stratigraphy, till analysis, core counts and comparison for other till studies.	Dispersal from 2 to 40 km down	Key paper defining the 6 till in Lapland and the till from previous related to them.	Hirvi (1977)

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TABLE 20.2: CONTINUED.

Location	Mineralization	Age	Host Rock	Alteration	Comments	References
1.	Magmatic	P-1	Granite	Hydrothermal	See also 2. and 3.	Johnson et al. (1988)
2.	Magmatic	P-2	Granite	Hydrothermal	See also 1. and 3.	Johnson (1988)
3.	Magmatic	P-1	Granite	Hydrothermal	See also 1. and 2.	Johnson (1988)
4.	Magmatic	P-2	Granite	Hydrothermal	See also 1. and 2.	Johnson (1988)
5.	Magmatic	P-2	Granite	Hydrothermal	See also 1. and 2.	Johnson (1988)
6.	Magmatic	P-1	Granite	Hydrothermal	See also 1. and 2.	Johnson (1988)

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TABLE 10.1: CONTINUED.

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EXPLORATION '87 PROCEEDINGS
GEOCHEMICAL METHODS: THEIR APPLICATION TO ORE EXPLORATION

TABLE 30.3: CONTINUED.

Location	Mineralization	Study Type	Sample Media, Fractions and Elements	Shape and Size (L x W) of Dispersal Train	Comments	Reference(s)
31. Dalecarlia, Central Sweden	Cu, Pb and Zn	A-1	Till; HbMc, Magnetite separated and analysed for V, V, Cr, Ni, Mn, Zn and Cu	From 1 km to 5 km long	Compared chemistry of magnetites from tills and different bedrock sources to arrive at a signature for magnetite derived from base metal mineralization.	Granath (1983)
32. Falun Area, Central Sweden	Cu, Pb, Zn and Ag	A-1	Till; <63 µm, Cu, Pb and Zn. Till fabrics measured and boulders mapped.	Subsided, 2.2 km x 100 m.	Commented on the influence of old preserved tills, exotic debris and sampling depth on till geochemistry and boulder tracing.	Eriksson (1983)
33. Hagfors, Central Sweden	W	B-1	Till; <500 - 100 µm, <100 µm and HbMc. W. Counted HbMc for scheelite grains. Analysed thorus for W.	Subsided, 1.6 km x 200 m.	Recommended sampling of till and analysis of the HbMc for W at both regional and follow-up stages as most cost effective exploration procedure.	Toverud (1984)
34. Auteuil, S.E. Normandy	AsA	B-1	Till, up to 11 grain size fractions. Wide range of major and trace elements. Grain size analysis. Compared to chemistry and grain size of source rocks.	AsA	Showed that the texture, facies and mineralogy of till should be considered when choosing a grain size range for geochemical analysis.	Haldorsen (1977, 1983)

TABLE 10.4: A SUMMARY OF DRIFT PROSPECTING AND RELATED OVERBURDEN STUDIES IN IRELAND AND THE U.S.A. (1977 - 1987) (STUDY TYPE: A - REGIONAL - 1 - RECONNAISSANCE, 2 - DETAILED; B - RESEARCH - 1 - ORIENTATION, 2 - FOLLOW-UP; C - EXPLORATION CASE HISTORY. HMC - HEAVY MINERAL CONCENTRATE, BCD - REVERSE CIRCULATION DRILLING.)

Location	Mineralization	Study Type	Sample Media, Fractions and Elements	Shape and Size (L x W) of Dispersal Train	Comments	Reference(s)
1. Lough Derg, County Galway, Central Ireland	Pb	B-1	percussion drill with rope through bit used to sample till, < 177 µm, Cu, Pb, Zn and Ba.	Ribbon, 600 to 1000 m long and 1 to 2 m thick.	Three dimensional study of a dispersal train. Several sections parallel to ice flow show the internal structure of the train.	Miller (1986)
2. Eastern County Offaly, E. Central Ireland	Pb and Zn	B-1	Soil sample, wet on till, Fe, Mn, Cu, Pb, Zn, Ni, Cd, U, Co, Mg, Ba and Organic C.	> 200 m x 75 m.	Shows that a proglacial regolith could produce a dispersal train; the regolith survived glaciation.	Maurice and Meyer (1972)
3. Asuca, Ireland	Pb and Zn	B-1	B-horizon soil and till sampled with a percussion drill, < 180 µm, As, Sb, Bi and Se.	Rich	The pathfinder elements As, Sb, Bi and Se were anomalous in soil and till. Till geochemistry was more useful than soil geochemistry.	Blair and Hale (1983)
4. Central Plain, Ireland	Pb and Zn	B-1	Percussion drill and power auger used to sample till, Multi element - including Pb, Zn, Ba, V, Mn, Ag, As and Sb.	Wide fan related to ice ice flow gives a dispersal train 6 km long.	A dispersal train in till anomalous in Pb and Zn underlay peat and other sediments. Drilling was required to map it.	Newrick and Roper (1978)
5. Ireland	Various	B-1	Soils and till - review of previous work.	Flame to ribbon, varying from 200 to 1000 m long.	Documented the change from soil to till sampling near surface and at depth from 1971 to 1981.	Coxeter (1982)
6. Trudent Glacier, Alaska, U.S.A.	Unknown	B-1	Medial and lateral moraine, fine grained material - HMC, Ag, As, Cr, Co, Mn, Ni, Pb, Sb, Sn, W and Zn. Boulder, cobble and pebble samples also were collected and counted etc.	Rich	Shows how the geochemistry and petrology of moraine debris could be used to evaluate the geology and mineral potential of ice-valley catchment areas.	Stephens et al. (1982)
7. Duluth Complex, Minnesota, U.S.A.	Pt, Pd and Au	A-2	Edgar sediments, < 63 µm and HMC, wide variety of elements.	Rich	Evaluated the geochemistry of Edgar sediments and found anomalies representing future up.	Morton and Eng (1985)

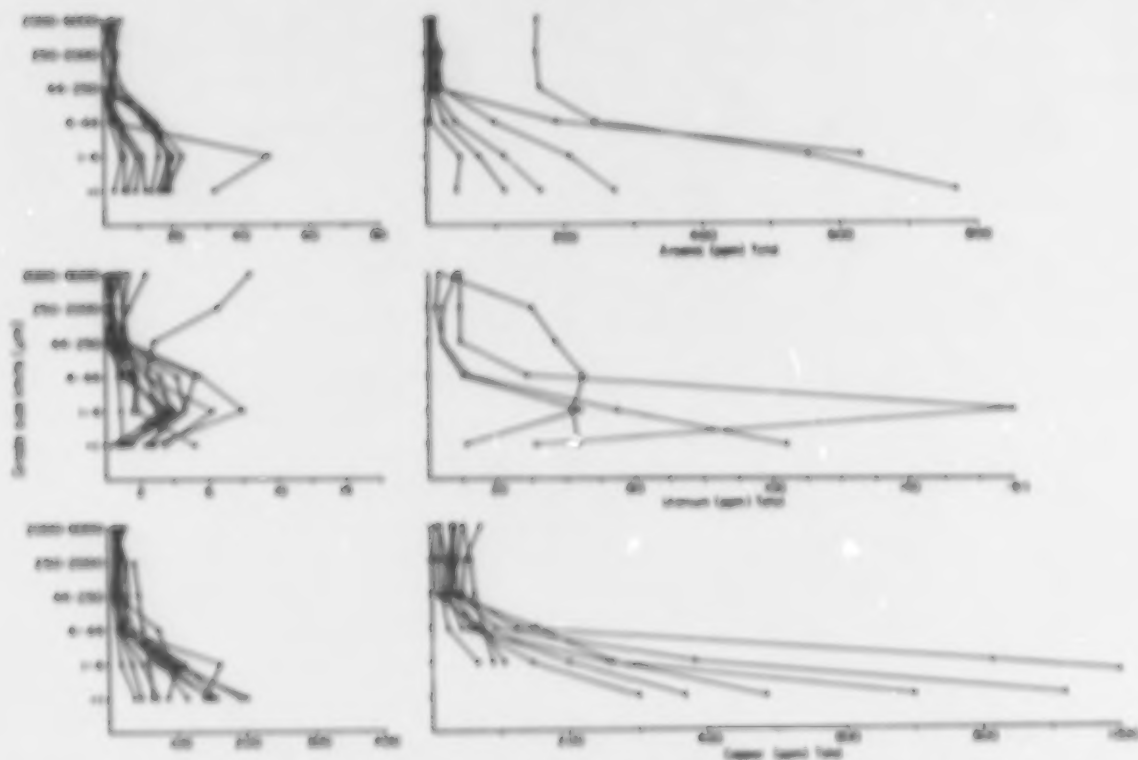


Figure 10.9. Abundance of Cu, U and As in different grain size ranges in a variety of till samples from the Canadian Shield (after Shills 1986a). Samples in right-hand figures considered to be anomalous; those on left present background. Each line represents one sample. Concentrations are from perchloric acid leach and represent "total" metal.

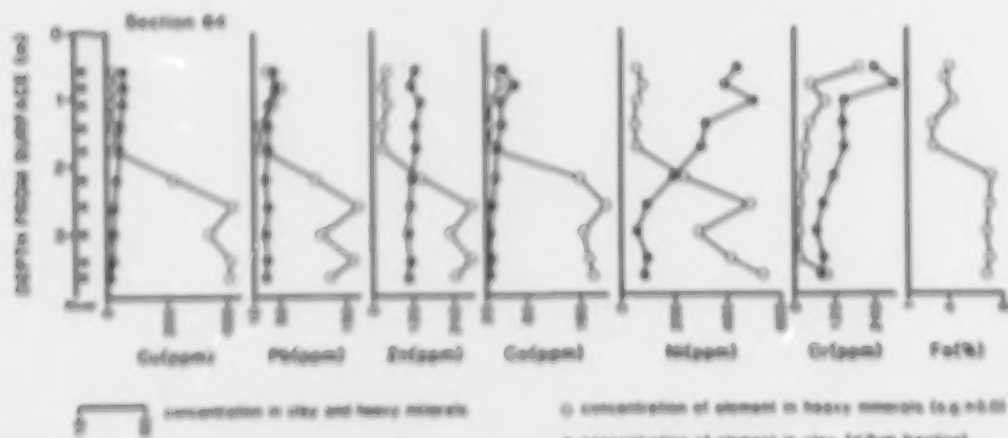


Figure 10.10. Chemistry of till fractions in a section of acidized and unacidized till, southeastern Quebec (Shills, Geological Survey of Canada, Ottawa, personal communication, 1988).

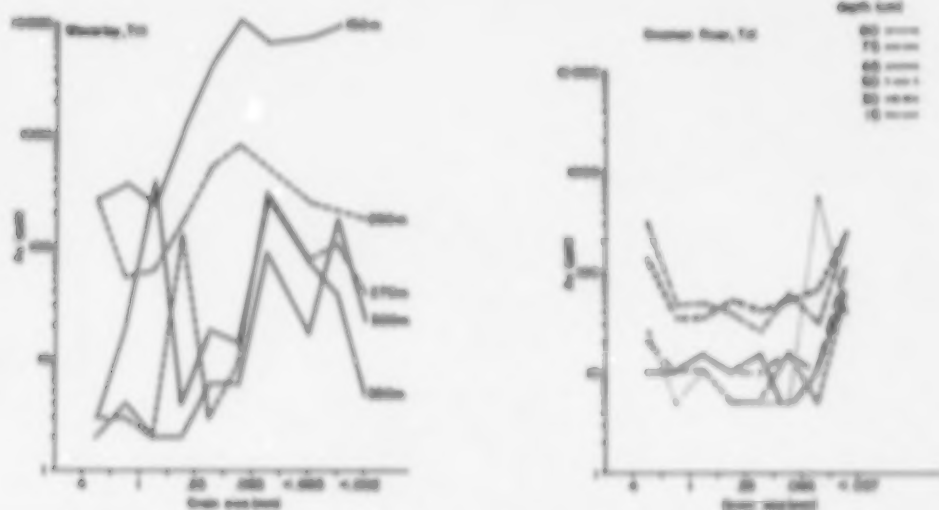


Figure 10.11. Abundance of gold vs. grain size of analysed fraction of till at different distances down-ice from a gold deposit at Waverley, Nova Scotia (after DiLabio 1982a) and at varying depths below surface in a dispersal train at Onamen River, Ontario (after DiLabio 1983).

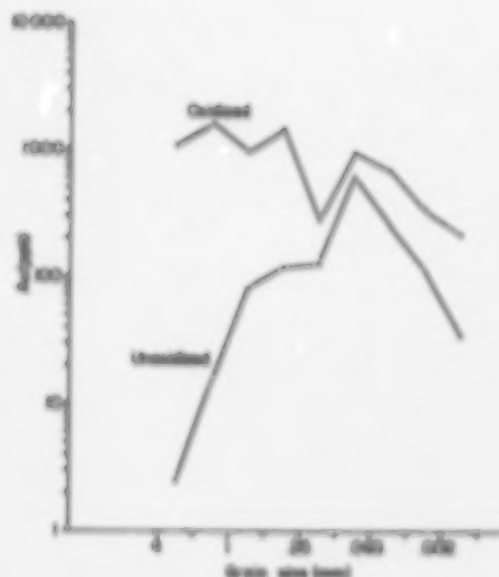


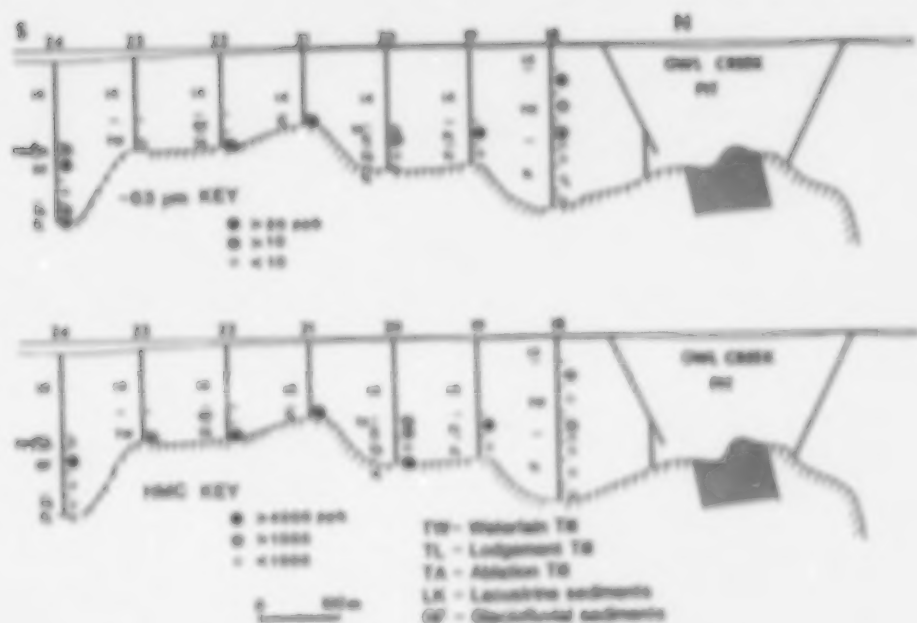
Figure 10.12. Abundance of gold vs. grain size of analysed fraction of unoxidized till and its oxidized equivalent at the Owl Creek Gold Mine, Timmins, Ontario (DiLabio 1983).

contrast and absolute levels of gold in the $<63 \mu\text{m}$ fraction are lower. On the other hand, for Hemlo type mineralization (Figure 10.13), they found that anomalous heavy mineral concentrates are restricted to the area right over the deposit and show little dispersal down-ice. The $<63 \mu\text{m}$ fraction shows significant down-ice dispersal. Thus, fine fraction and heavy mineral concentrate analyses can provide different, often complementary, information.

It should be apparent that the routine use of -80 mesh material for till geochemical surveys should be carefully examined. Orientation surveys should be conducted to determine the optimum size fraction to use. Fine grained materials appear to be the best media in many instances. The nature of the weathering history of the material also determines the appropriateness of the grain size to be used. The use of fine fraction and heavy mineral concentrate fraction geochemistry to complement each other may well increase exploration effectiveness and reliability.

DRIFT PROSPECTING

Drift prospecting is the use of data on the geochemistry and lithology of glacial sediments (mainly till) to identify economically significant components in the sediments and to trace them up-ice to their bedrock sources (DiLabio, in press). The concept of predictable patterns within dispersal trains (e.g. exponential decay as shown in Figure 10.1 and shape of trains as shown in Figure 10.3), when considered during the design of a geochemical exploration program, will influence the choice of sample types, the sampling plan, the analytical scheme, and the interpretation of the data. Compared to other types of geochemical



HEMLO

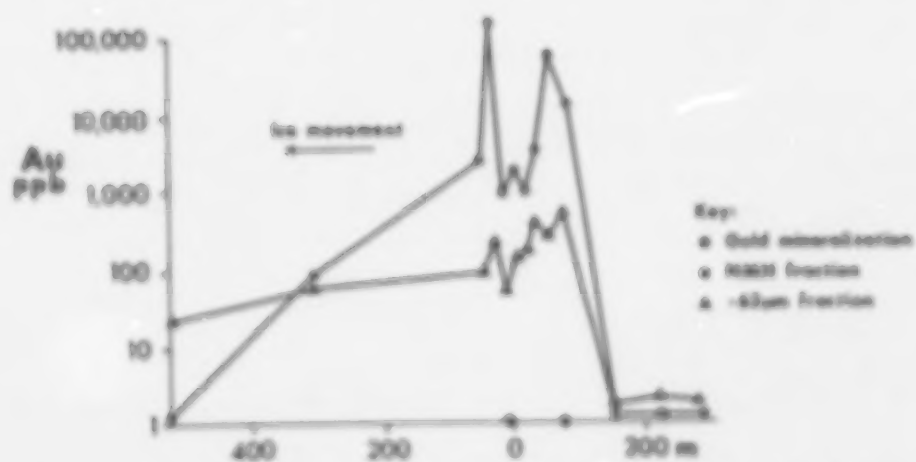


Figure 20.13. Comparison of the Au distribution in the heavy mineral concentrates and the <63 µm fractions of HMC at the Owl Creek Gold Mine, Timmins, Ontario; and, associated with Au mineralization at Hemlo, Ontario (from Ishiy and Nickel 1987).



Figure 10.14. Drift prospecting and related overburden studies in Canada (numbers on map refer to Table 10.1).

anomalies, once a dispersal train has been detected, it can be traced more easily up-ice to its source because simple clastic dispersal is the main mechanism involved in the formation of a train.

In the last decade many studies of dispersal trains have been documented within Fennoscandia and Canada. Details of these studies/case histories are summarized in Tables 10.2, 10.3, and 10.4 and their locations are shown on Figures 10.14 and 10.15. It is impossible to go into much depth of discussion for all of these examples so we have been forced to be selective in those discussed more fully in the following text. We have focused mainly on gold, a commodity currently of prime exploration interest, and on studies with which we are most familiar and which seem to best make the points we wish to emphasize such as: understanding ice movement directions, glacial stratigraphy and bedrock topography as they control the nature of glacial dispersal, and the resultant dispersal trains.

In the Strange Lake area of Labrador (see Table 10.2 #10), a large glacial dispersal train of debris

(McConnell and Berman 1987) from a peralkalic complex containing Rare Earth Elements, niobium, zirconium, yttrium, beryllium and lithium is clearly shown by airborne radiometric data (equivalent thorium). The dispersal train from the peralkalic complex was originally located by a uranium anomaly in a regional reconnaissance lake-sediment survey (Geological Survey of Canada 1979). It is important to note that depending on the nature of a source, for example its radioactivity, and the amount of bedrock exposure and/or thickness of overburden cover, remote techniques (e.g. airborne radiometrics) or other regional reconnaissance methods (e.g. lake-sediment geochemistry) can detect glacial dispersal trains. Detailed till sampling carried out on the Strange Lake dispersal train found that lead as well as niobium, yttrium, and zirconium in the <63 μ m fraction of the till best defined the dispersal train and outlined the details within it (Figure 10.16).

At Simon Brook, New Brunswick, Snow and Coker (1987) (see Table 10.2 #20) demonstrated that the tungsten mineralization on the property is



Figure 30.15. Drift prospecting and related overburden studies in Fennoscandia (numbers on map refer to Table 30.2).

detectable by tungsten in all size fractions of the till, as shown for the ~ 200 mesh ($<75\mu\text{m}$) and HMCs from trench 1 located immediately down-ice from the mineralization (Figure 30.17). The dispersal train from the tungsten mineralization, based on whole till (~ 10 mesh (<2 mm) ground to ~ 200 mesh ($<75\mu\text{m}$)) truncates against a quartzite ridge. It appears that debris, containing components of the tungsten mineralization, has been sheared up into the glacier and carried 8 km down-ice before eventually being deposited. Trenching through the transported lenses of till (anomalous in tungsten), and sampling and analyzing the underlying local granitic till and bedrock revealed no tungsten mineralization. This example clearly illustrates the importance of understanding the nature of glacial transport and deposition, as well as the stratigraphy, of the glacial overburden.

A reverse circulation overburden drilling program carried out at the Golden Ford gold deposit, Casa Berardi, Québec by Saurbrey *et al.* (1987) identified a thin lower till containing anomalous gold values and abundant gold grains (see Table 30.2 #32). Of note was the discovery that glacial dispersal of gold was very limited, in the order of 200 to 400 m. This was because the ice that deposited the lower till moved subparallel to the strike of the mi-

neralized structure, itself recessive and a bedrock trough, further confining the dispersal train.

In Timmins, Ontario, a reverse circulation and rotational drilling program was carried out by Bird and Coker (1987) at the Owl Creek gold mine (see Table 30.2 #45). This revealed a deep and complex overburden stratigraphy with up to four glacial sediment packages, each with different ice movement directions (Figure 30.18). In the lowest (Older) till, on bedrock, dispersal is very local, being truncated against a bedrock ridge. The highest gold levels in till are adjacent to the subcropping gold mineralization. The overlying till (Matheson), has not been in contact with mineralization or bedrock, and has derived its gold from the lower (Older) till. This dispersal train is longer, approximately 600 m, and the area of maximum gold in till is displaced some 300 m down-ice from the subcropping gold mineralization. Again, the effect of bedrock topography on glacial dispersal, and the importance of understanding the glacial stratigraphy and ice movement directions in an area are emphasized.

In the Hemlo area, at the Page-Williams gold deposit - "A" mine, Olsson and Sheehan (1987) sampled the till using percussion drills with flow through bits (see Table 30.2 #47). They found that the exotic calcareous till gave little indication of the gold mineralization (Figure 30.19). The underlying locally derived limonitic till gave good response in all size fractions and HMCs, in gold, arsenic, antimony, molybdenum, mercury, tungsten, and barium, to the gold mineralization (Figure 30.19). Once again, dispersal was short (i.e. 200 m), partly because the deposit lies in the lee of a bedrock high and is protected, and partly because dispersal is truncated against a bedrock high down-ice.

A rotational overburden drilling program carried out by Averill and Zimmerman (1986) in northern Saskatchewan, located a dispersal train in which the HMCs from the till contained abundant native gold, gold-silver and copper, as well as galena, chalcocite, and pyromorphite, which led to discovery of the EP gold zone at Waddy Lake (see Table 30.2 #39). This classic dispersal train is ribbon-shaped with sharp edges (Figure 30.20). Of note is that the trend of the glacial dispersal train is 15° off the direction for ice movement indicated by glacial striae in the area.

Many countries have started to carry out regional reconnaissance till-sampling programs in order to aid mineral exploration and to provide baseline data for environmental, agricultural, geomedical and other disciplines. One outstanding example is the Nordkalott Project carried out by the Geological Surveys of Finland, Norway and Sweden (1986a, b, c, d, e, f, and 1987) north of 66° in these countries (Table 30.3). Several sample media, (including till) were collected and analyzed ($<63\mu\text{m}$ and HMC $>62 \leq 500\mu\text{m}$). Single element, principal component analysis and various types of interpreta-

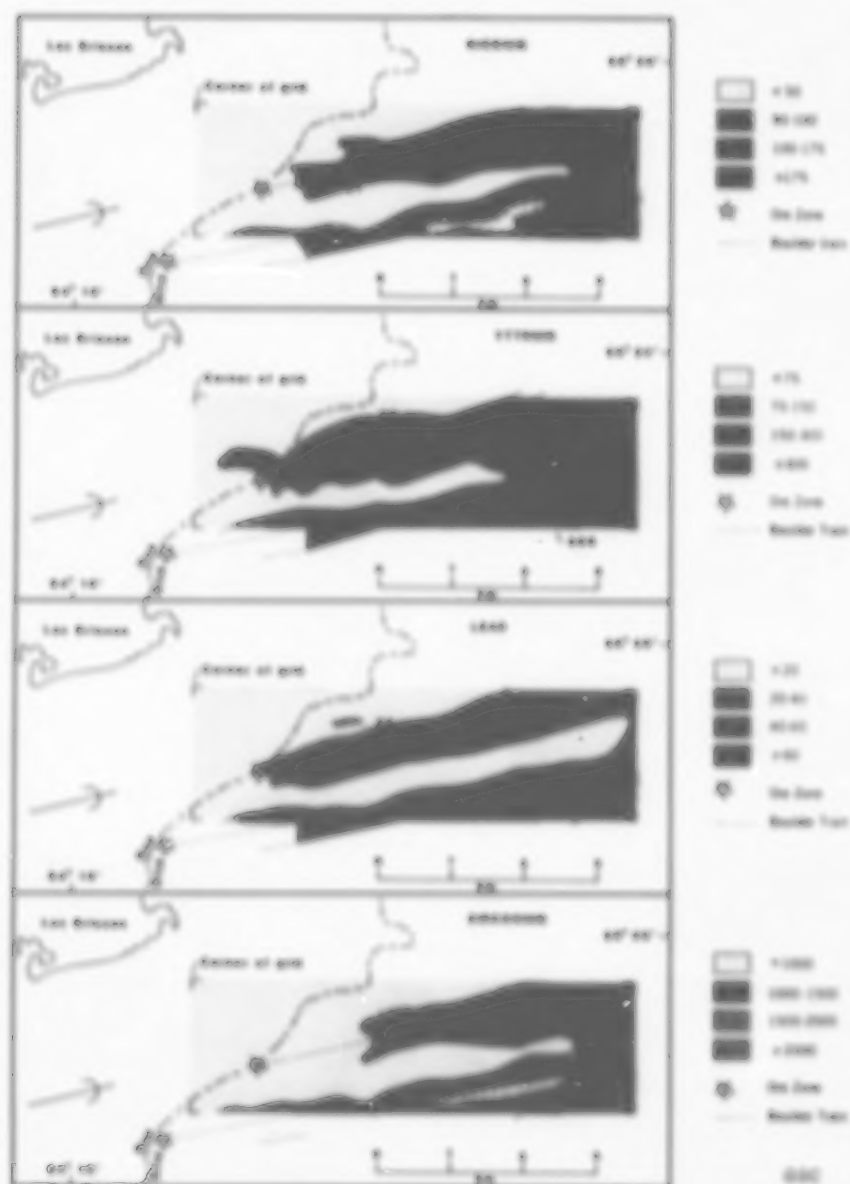


Figure DB.18. The Erongo Lobe disposal unit, Lebrador, mapped by the abundance of trace elements in the 100 µm fraction of soil.

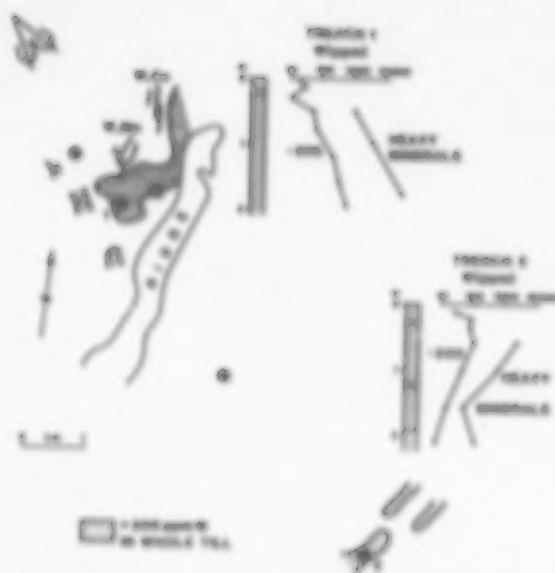


Figure 10.17. Tugboat in till at Isaac Brook, New Brunswick (after Snow and Cooper 1987).

tion and auxiliary data (i.e. geology, magnetic, mineral deposits, etc.) maps were produced. As an example, the regional distribution of copper (DMC) primarily depicts areas of granitoid, areas of mafic to intermediate intrusives and volcanics as well as areas of copper mineralization (Figure 10.21).

A regional till sampling and surficial mapping program was carried out by Kaszycki and Gilabert (1986a, b) in northwestern Manitoba (see Table 10.2 #31). The distribution of zinc in the <2 μ m fraction of the till clearly depicts the Lynn Lake greenstone belt and other similar geologic features. However, the regional distribution of zinc is controlled by the westward limit of dispersal of carbonates from Hudson Bay, as shown by the western limit of carbonate dispersal (i.e. CaCO_3 content of till, Figure 10.22, Kaszycki, in press).

Another glacial sediment type sometimes used in mineral exploration is esker sediment. The gravel and sand found in eskers can be considered as the sorted coarse sediment that remains when the mud is washed out of till by subglacial and englacial streams. Esker sediments are then second-cycle sediments (second derivatives of bedrock of Shultz 1978) and have been shown to reflect the geochemistry and lithology of the adjacent till where the indicator rocks and minerals survive transport in the esker system. Because eskers are widely spaced and samples from them represent small areas along their length, they are best used in reconnaissance sampling or in detailed sampling where they cross

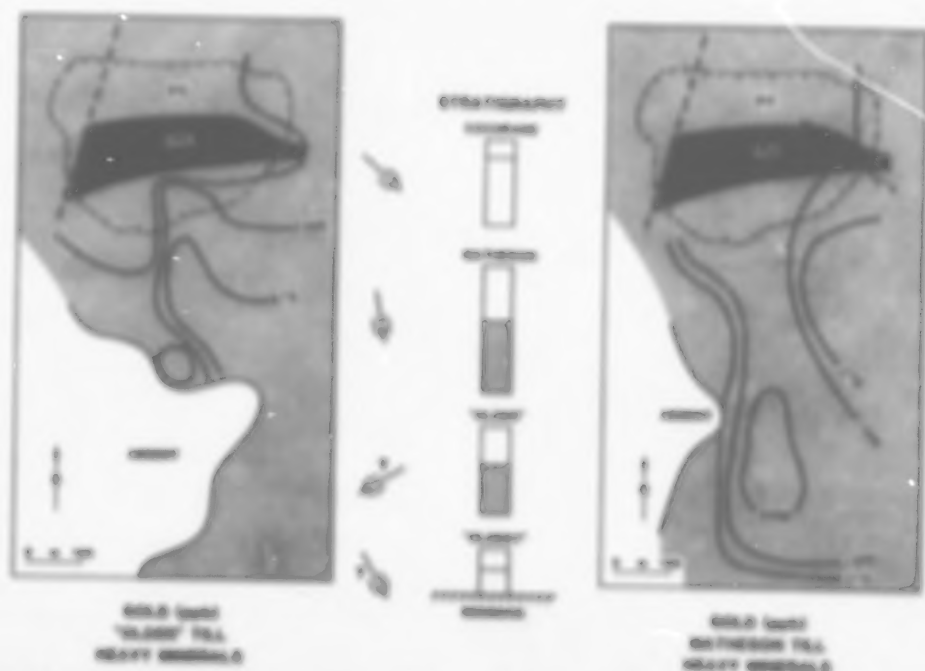


Figure 10.18. Gold levels in heavy mineral concentrates from the "Globe" and Markham Tills at Owl Creek gold mine, Ontario, Ontario (after Bird and Cooper 1987).

Location	Gold grade	
	-100 mth	Heavy Mineral
Human (0.1 m)	15.00	
Upper Minnion		5.75
100 (0.5 m)		5.00
Lower Minnion		0.10
100 (1 m)		
Lower Minnion	10.00	0.10
100 (0.5 m)		
Old Minnion	20.00	20.00
100 (0.5 m)		
Average (1.0 m)	1.1000	1.1000

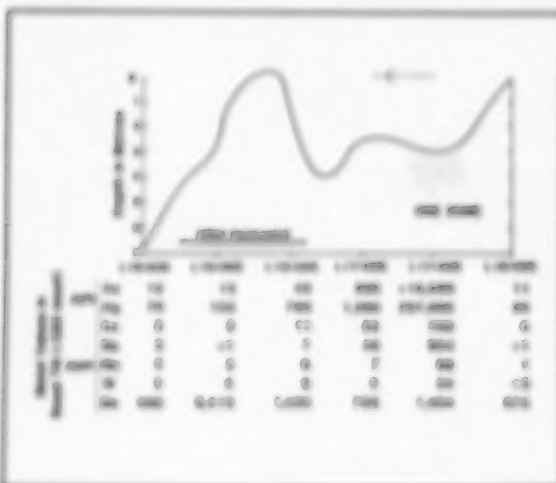


Figure 26.17. Fogo - Williams gold deposit—0.1 m zone. Human, Ontario: Range of gold values in human, waste calcareous till and local limestone till from four pits over the mineralization; and, bedrock topographic profile and geochemistry across the mineralization (from Gibson and Shaker 1987).

favourable geological structures. Some examples of the use of other indicators in mineral exploration include work by Lee (1961, 1962), Shiba (1972b, 1984b), Baker (1981, 1982), and Martin and Eng (1983).

APPLICATIONS TO ENVIRONMENTAL ISSUES

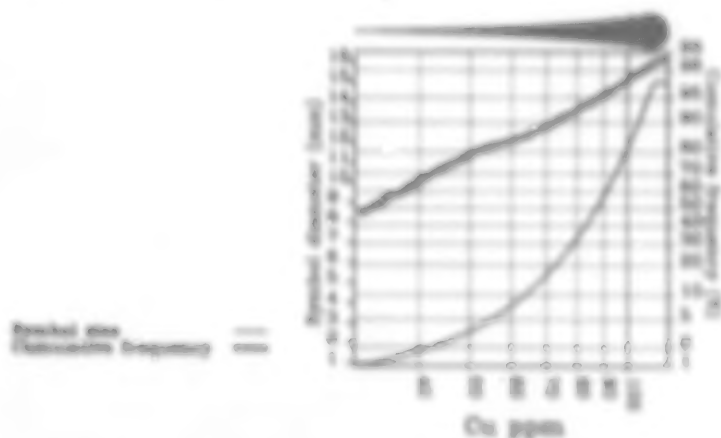
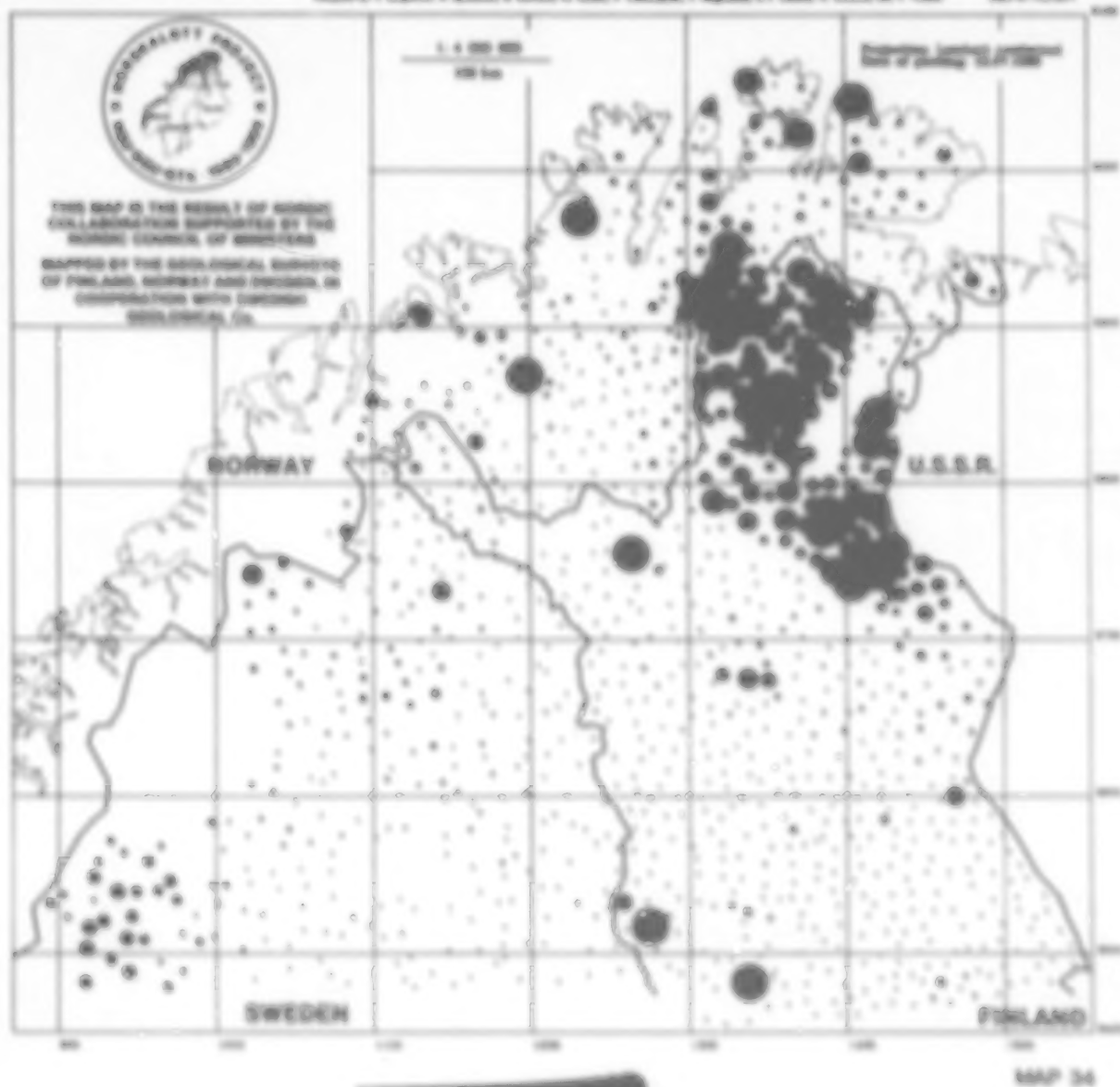
Geochemical and biological data on glacial and postglacial sediments have been used recently to estimate the sensitivity of terrain to acid precipitation and to identify areas that are naturally enriched in potentially noxious trace elements. For example, Coker and Shiba (1979), Benes and Shiba (1980), Shiba (1984a) and Egeles and Wyon (1983) all demonstrated how data collected for mineral resource evaluation, to aid bedrock mapping, and to delineate natural regional geochemical trends also



Figure 26.26. Glacial dispersal from the EP gold area, Waddy Lake, Eastern Ontario (from Anon and Zimmerman 1986).

could be used to detect existing or potential environmental disturbances.

In a study designed primarily to identify areas that might be sensitive to acid precipitation, Benes and Shiba (1983) sampled till and other glacial sediments over an area of 15 000 km² covering the Frontenac Arch of southeastern Ontario. This area lies within the plume of acid precipitation in eastern North America. The arsenic content of the samples (Figure 26.23) is one example of data on a potentially noxious element that was mapped in this survey (Hordbrech et al. 1986). Anomalous arsenic levels outline one of the original gold mining areas of Ontario, within the Grenville metasedimentary belt in the eastern part of the Frontenac Arch, and are also found along the southern edge of the exposed Precambrian bedrock. These anomalous levels highlight areas in which arsenic might be remobilized into surface water and groundwater if soil acidity was increased by acid precipitation. The anomalous levels



Nordkelt project
Geochemistry
TILL
Heavy minerals
Cu

See Section 10.1, 10.2, 10.3
Number of samples: 100
Laboratory: 1000
No. of analyses: 1000

Figure 10.21. The distribution of Cu in the heavy mineral fraction of till in the Nordkelt Project area (Geological Survey of Finland, Norway and Sweden 1990).

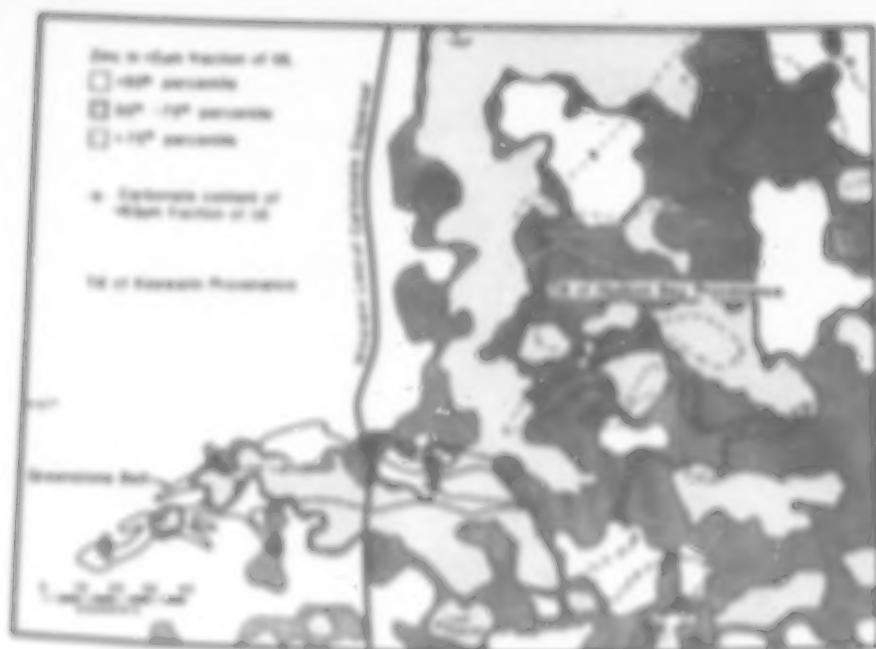


Figure 16.22. Anomalies and levels in soil in relation to bedrock geology and to the presence of arsenic calcareous debris in the soil in the Lynn Lake-Lake Rapids area, Manitoba (Rasmussen, in press).



Figure 16.23. Arsenic content of soil on the Franciscan Arch, southeastern Ontario (after Rasmussen and Shute (1982)).

are also significant in terms of mineral exploration because arsenic is considered as a pathfinder for gold, and consequently, the elevated levels outlining areas of known gold occurrences and other land with potential for gold mineralization.

Geochemical data are increasingly used in prospecting and agriculture to outline areas of natural enrichment or depletion of various trace elements or essential micronutrients (Bolskan et al. 1980). These examples show the multiple uses for geochemical data on surficial sediments, uses which might not have been considered when the surveys were originally designed.

CONCLUSIONS AND FUTURE TRENDS

A number of points have been emphasized in this paper. Many are areas in much need of further work and research. These include the need for:

1. Regional studies of soil provenance, including the effects of exotic drift on local geochemistry
2. Correlation of tills in areas of complex stratigraphy and assignment of ice-flow directions to tills
3. Investigation of the composition and weathering behaviour of ore minerals, particularly gold and platinum group elements, in order to design better sampling and analytical schemes
4. Demonstration of the use of till geochemical data as a base for other data sets such as biogeochemistry and environmental studies, etc.
5. Development of more cost effective drilling systems, particularly in areas of overburden overburden thicknesses (i.e. 10 - 20 m).
6. Education and training of geologists in geochemistry and Quaternary geology and a commitment by senior explorationists and exploration managers to the use of qualified people to carry out till surficial geochemical and overburden drilling programs.

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A great many people from the Canadian Federal and Provincial Geological Surveys, the Fenoscandian Geological Surveys, as well as from the mining community have contributed data, reports, slides and figures to this review paper. Although too many in number to individually mention we gratefully acknowledge their contribution to this paper. We thank W. W. Shill for his constructive comments on the manuscript.

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31. Regional Geochemistry Based on Stream Sediment Sampling

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ABSTRACT

Multielement geochemical surveys based on stream sediment samples provide a means of preparing systematic regional data which can be integrated with satellite imaged information, geophysical, and geological information using digital image analysis. This gives a basis for regional geological (lithofacies) mapping and for the incorporation of geochemical data into metallogenic models and artificial intelligence systems for mineral exploration. The application of regional geochemical data for these studies, and the direct detection of mineral deposits is discussed using examples from Britain, North America, Fennoscandia, and elsewhere.

Published geochemical data sets are reviewed and it is suggested that stream sediment samples, collected to approximate the average composition of catchment bedrock, provide the most generally useful data sets. Petrogenetic elements including the rare earth elements (REE), Y, Zr, Ti, K, Rb, Li, Ba, Sr and their ratios provide information on the tectono-stratigraphic setting of ore deposits, and should be determined in addition to ore-forming metals and pathfinder elements (such as As, B, Sb, Se, and Bi). Special sampling media and analytical procedures can be used to improve the detection of some ore deposit types.

Limitations to the application of stream sediment sampling in different terrains including the arid and humid tropics, and glaciated regions are considered; and modifications to standard stream sediment sampling procedures which can be used to extend the range of the method are described.

INTRODUCTION

In many parts of the world, geochemical mapping based on stream sediment sampling has become an established method of mineral exploration both on the reconnaissance and more detailed scales. Stream sediments provide a robust sample that is easy to collect and analyze; suitable drainage systems exist in most terrains; and useful results can be obtained in a range of climatic regimes. Moreover, the basic method can be modified readily with the collection of different fractions or heavy mineral concentrates

to enhance anomalies for particular ore deposit types. Developments in regional geochemistry aimed at the direct detection of orebodies undergoing weathering and erosion have been reviewed by a number of authors (e.g. Meyer *et al.* 1979; Thompson 1982; Govett 1986). It is the representative nature of stream sediment samples which distinguishes them from most other sampling media. They approximate composite samples of soil, weathering products, and rock upstream from sampling sites and are representative at the scale of drainage basins. It is this property which provides the means of preparing systematic geochemical data sets over large regions of the earth's crust. Such data sets provide a unique picture of trace element distribution that reflects discontinuities and change in lithology which may not be apparent from the geological map and which can be used to characterize the geochemical setting in which ore deposits occur. Regional geochemical data sets are increasingly used with satellite imaged, digital geophysical, and geological data for exploration, resource evaluation, and mineral deposit modeling studies.

Some of the advantages and limitations of regional geochemical mapping are compared with geophysical and conventional geological mapping in Table 31.1. The applications of regional geochemistry based on stream sediment sampling for fundamental

TABLE 31.1. SOME ADVANTAGES OF REGIONAL GEOCHEMISTRY.

- (1) Low cost per unit area compared with that for conventional geological mapping and most geophysical methods.
- (2) Basic data collected are numerical and, therefore, objective; less skill required for sampling than in conventional geological mapping.
- (3) Data for 30–50 parameters (chemical elements) can be provided and used singly or in combination; with most geophysical methods the number of parameters obtained is relatively small.
- (4) Mineral deposits are concentrations of chemical elements and can often be recognized directly, whereas geophysical and remote sensing methods respond to phenomena which, with a few important exceptions, are only indirectly indicative of mineralization.

research in understanding ore genesis are fully described elsewhere (Plant *et al.*, in press).

In this discussion, we consider the characteristics of different surface environments as a basis for the development of optimum sampling strategies for; a) representative sampling for high-resolution geochemical mapping, and b) the enhancement of anomalies for different ore deposit types. Developments in analytical procedures and data processing are also reviewed.

DIFFERENT SURFACE ENVIRONMENTS

GENERAL

Conditions in the surface environment represent a complex interplay of climatic, physiographic, biological, anthropogenic, and geological factors and hence are highly variable from the local to continental scale. Moreover, climates have changed frequently, and often profoundly, since the mid-Tertiary (Butt and Zeegers, in press). Whereas large areas in the temperate and higher latitudes are dominated by the effects of Pleistocene glaciation, the warmer lower latitudes have regoliths and associated landforms related to past (or continuing) periods of deep weathering and lateritization under seasonal tropical conditions. Such conditions were probably geographically widespread from the Cretaceous, or earlier, until the mid-Tertiary, and subsequently contracted to the present near-equatorial latitudes. Similarities in dispersion characteristics may be present over extensive regions, and some of the characteristics of different environments are discussed here as a basis for considering alternative sampling procedures designed to prepare representative samples for geochemical mapping, or to enhance anomalies related to orebodies undergoing weathering and leaching.

Considering cool temperate regions such as those of northwestern Europe, which are characterized by relatively high rainfall and high levels of organic activity, two main types of surface environment can be distinguished. Firstly, there are areas of impervious crystalline rocks where water/rock contact times are low, and low concentrations of "major" cations and anions in surface water are reflected by exceptionally low conductivity values (Plant and Moore 1979; Steenfelt 1987). Concentrations of H^+ ions generally exceed those of Ca^{2+} ions, and surface conditions are predominantly acidic (partly as a result of organic activity) with large areas of peat bogs and/or acid soils. Oxidation of organic detritus in cool wet climates is generally slow and accumulations of peat and poorly drained acid soils give rise to reducing conditions. The acidity may be further increased by precipitation from air masses containing acid gases, such as SO_2 from industrial sources. In such acid reducing conditions iron and manganese are soluble, but precipitate near

to the surface in iron pans and in streams in equilibrium with atmospheric oxygen, resulting in the formation of hydrous manganic and ferric oxides. The ability of these oxides, together with organic material, to absorb large quantities of trace elements, especially the first row transition elements and barium, is an important control on trace element concentrations in stream channels. Younger or uplifted mountain fold belts represent an extreme variant of this type of regime although the organic component may decrease at high altitude.

Secondly, there are lowland areas consisting of agricultural soils underlain by permeable sedimentary rocks, which have surface waters predominantly of the $Ca^{2+} - HCO_3^-$ type. The Eh and pH and levels of the major cations Ca^{2+} , Na^{2+} , Mg^{2+} and K^+ , and anions are generally higher than in areas of crystalline rocks with a consequent increase in water hardness, while the content of organic acids is low since they are precipitated under such conditions. Mobilization of heavy metals by complexation and adsorption on colloidal organic matter, manganese, and iron is also correspondingly reduced.

At higher latitudes, particularly in areas of poorly drained permafrost, the accumulation of organic matter may increase further giving rise to extensive areas of muskeg swamp, for example in Northern Scandinavia, Canada, and the USSR. Finally, in arctic/sub-arctic areas such as North Greenland, which have a dry climate and where vegetation cover is poor or almost totally lacking, weathering and transport are almost totally mechanical (Steenfelt and Kunzendorf 1979), and the effects of organic matter and of manganese and iron oxide scavenging of trace elements in stream channels is correspondingly minor. The chemical dispersion of elements is generally assumed to decrease in cold climates, particularly in areas where a thick permafrost boundary exists, but the detection of haloes around silver-arsenide veins even in snow (Jonasson 1976) suggests that some form of chemical dispersion may be important. One of the most significant problems of high latitudes is the presence of thick glacial deposits, particularly where the material represents exotic tills. Detailed studies in Scotland (Plant *et al.* 1984a), Canada (Shilts 1984), and Finland (Björklund *et al.* 1976) suggest, however, that even in areas of extensive exotic till sheets, geochemical anomalies may be displaced by less than 2 to 3 km, which is relatively insignificant at reconnaissance or regional geochemical mapping scales. This partly reflects the re-incision of stream networks during post-glacial uplift as a result of isostatic readjustment, and partly the local derivation of till detritus.

In contrast to cold and temperate climates, tropically weathered terrains commonly comprise thick (up to 100 m) sections of local, but deeply leached, overburden. Oxidation of organic matter may be intense with pH varying from acidic values in

areas of heavy rainfall/dense rain forest to slightly acidic to alkaline in more arid terrains, where surface to near-surface water may be saline and dominated by chloride species. The former terrain type is characteristic of parts of Central Africa and Brazil, where extensive plateaux of low relief are characterized by deeply leached soils in which aluminosilicates are broken down to give a dissolved phase, mainly cations and silicic acid, and a residue consisting of clay minerals with high Al/Si ratios, secondary iron oxides and resistate minerals. These areas generally grade into seasonally wet/dry regions such as parts of Africa and South America, which are characterized by lateritic soils. In both the permanently humid and seasonally wet/dry tropics there may be pronounced short (e.g. cyclones) and long (e.g. droughts) term climatic fluctuations superimposed on the normal pattern of seasonal variation. Finally, in semiarid to arid regions, such as much of central Australia and north and southwest Africa, there is more variable surface cover, sometimes with extensive areas of aeolian sands. Here, and in the seasonally wet/dry terrains, intermittent, but frequently turbulent, water flow along the drainage network promotes dispersion and abrasion, so that the coarse sediment fraction is representative of the immediate surroundings while progressively finer material has a more distal provenance. The finest fractions in the more arid regions may contain a wind-borne com-

ponent which dilutes the geochemical signature from water-borne sediments (Zeegers *et al.* 1985).

STREAM SEDIMENT COMPOSITION AND TRACE ELEMENT BEHAVIOUR IN DIFFERENT SURFACE ENVIRONMENTS

In general, the proportion of detrital, colloidal, and precipitated coatings and soluble components and their compositions vary in different regimes. The detrital component of stream sediments is generally more important at higher latitudes, particularly in areas of high relief, and in cold and hot arid environments not subjected to deep chemical leaching. In contrast, clays are likely to be of greater importance at lower latitudes, and organic precipitates in cool temperate areas, particularly those underlain by impervious crystalline rocks. Iron oxides generally reflect acidic surface conditions typical of leached, tropically weathered profiles, or surface precipitates in organic-rich temperate environments. Surface waters also range from dilute acid solutions in areas of high precipitation at high latitudes/altitudes to $\text{Ca}^{2+} - \text{HCO}_3^-$ solutions in areas underlain by porous sediments. Highly saline chlorine-dominated brines characterize arid conditions, while SO_4^{2-} -enriched waters reflect oxidation of sulphides, the presence of red bed sandstones containing such phases as gypsum, or industrial contamination.

TABLE 31.2. RELATIVE MOBILITIES OF ELEMENTS IN THE SECONDARY ENVIRONMENT (AFTER ANDREWS-JONES 1968).

RELATIVE MOBILITY	ENVIRONMENTAL CONDITIONS			
	Oxidizing	Acid	Neutral-Alkaline	Reducing
VERY HIGH	Cl, I, Br S, B	Cl, I, Br S, B	Cl, I, Br S, B Mo, V, U, Se, Re	Cl, I, Br
HIGH	Mo, V, U, Se, Re Ca, Na, Mg, F, Sr, Ra Zn	Mo, V, U, Se, Re Ca, Na, Mg, F, Sr, Ra Zn Cu, Co, Ni, Hg, Ag, Au	Ca, Na, Mg, F, Sr, Ra	Ca, Na, Mg, F, Sr, Ra
MEDIUM	Cu, Co, Ni, Hg, Ag, Au As, Cd	As, Cd	As, Cd	
LOW	Si, P, K Pb, Li, Rb, Ba, Be Bi, Sb, Ge, Cs, Tl	Si, P, K Pb, Li, Rb, Ba, Be Bi, Sb, Ge, Cs, Tl Fe, Mn	Si, P, K Pb, Li, Rb, Ba, Be Bi, Sb, Ge, Cs, Tl Fe, Mn	Si, P, K Fe, Mn
V. LOW TO IMMOBILE	Fe, Mn Al, Ti, Sn, Te, W Nb, Ta, Pt, Cr, Zr Th, REE	Al, Ti, Sn, Te, W Nb, Ta, Pt, Cr, Zr Th, REE	Al, Ti, Sn, Te, W Nb, Ta, Pt, Cr, Zr Th, REE Zn Cu, Co, Ni, Hg, Ag, Au	Al, Ti, Sn, Te, W Nb, Ta, Pt, Cr, Zr Th, REE S, B Mo, V, U, Se, Re Zn Cu, Co, Ni, Hg, Ag, Au As, Cd Pb, Li, Rb, Ba, Be Bi, Sb, Ge, Cs, Tl

TABLE 31.3. MAIN ELEMENTS FORMING STABLE CARBONATE, CHLORIDE AND SULPHATE SPECIES (AFTER LEVINSON 1974).

1. Carbonates - Cr, K, Na are soluble in water, others are insoluble or only sparingly soluble
2. Chlorides - Sb, Ba, Cd, Ca, Co, Cu, Fe²⁺, Fe³⁺, Pb, Mg, Mn²⁺, Ni, K, Na, Sn²⁺, Sr, Zn, Pt are soluble in water. Bi, Cr, Au⁺, Hg⁺, Ag are insoluble
3. Sulphates - Cd, Cr, Co, Cu, Fe²⁺, Mg, Mn²⁺, Ni, K, Na, Sn²⁺, Zn, Pt are soluble in water, others are insoluble or only sparingly soluble

Elements considered: Sb, Ba, Bi, Cd, Ca, Cr, Co, Cu, Au⁺, Fe²⁺, Fe³⁺, Pb, Mn²⁺, Hg⁺, Ni, K, Na, Sn²⁺, Sr, Zn and Pt.

The relative immobility of elements in different Eh-pH conditions, and the elements forming stable soluble Cl⁻, CO₃²⁻, and SO₄²⁻ species, are given in Tables 31.2 and 31.3. In humid environments, ore-forming and pathfinder elements are leached and re-precipitated as secondary phases or occur in detrital grains. Gold is a special case which until recently was considered to be resistant to chemical alteration in the surface environment. Detailed studies of the dispersion of gold in tropical terrain (e.g. Lecomte and Colin 1987) suggest that most is present as fine (<60 µm) particles formed by the dissolution of gold grains and re-precipitation and adsorption/complexation of secondary Au. Of the platinum group elements, Ir is the least mobile and can be used to determine the extent of remobilization of the other PGEs, Ni, Co, and Cu during weathering of basic lithologies (Taufen and Marchetto 1987). Of the elements used to indicate the tectonic setting of rock assemblages and water/rock interaction around orebodies, the high field strength elements such as the REE, Y, Th, Nb, Ta, Zr, and Hf are likely to be useful in most terrains since they are relatively resistant to alteration by chemical or biological processes. Other elements such as B, which may be incorporated in tourmaline as a result of mineralization processes, and which can be a pathfinder for gold in some types of epithermal deposits, may also survive deep leaching. The alkali and alkaline earth elements are likely to be deeply leached in regimes of chemical weathering at low latitudes, although they should provide useful information in terrains where dispersion is predominantly detrital.

Special element ratios such as Ga:Al, K:Rb, Ba:Rb, and Se:S and PGE patterns may be useful in most environments except those of intense chemical leaching. The REE patterns of the Pike's Peak granite of the southwest U.S.A., have been shown to be preserved in stream sediment samples (Howarth *et al.* 1981) and would be predicted to be stable in most surface environments on the basis of theoretical considerations (Taylor and MacLennan 1985). The B:Ga ratios may be useful in determining sedi-

ment-magma interaction, even in deeply weathered tropical terrain, if the B occurs in tourmaline (Taylor *et al.* 1987). The U daughter products and evidence of disequilibrium, e.g. equivalent U determined by gamma spectrometry compared with total U determined by methods such as delayed neutron activation, may provide particularly useful information on recent weathering processes (<1 million years), while Pb isotopic data may also be useful in detecting buried U, base metals, and some types of Au deposits (Gulson *et al.* 1987).

SAMPLING

GENERAL

Information on the characteristics of different surface environments can be used to prepare guidelines for sampling programs, although orientation studies should always be carried out before initiating regional geochemical surveys. Wherever possible, orientation samples should be collected from unworked mineralization, and rock types and surface environments representative of the region to be covered. Moreover, it is essential to consider at the outset the aims and objectives of the program. These might range, for example, from a requirement to prepare high precision, high resolution, multielement geochemical maps on the part of a national survey organization, to the completion of a rapid reconnaissance survey for Au mineralization by a small mineral exploration group. We therefore distinguish two main types of sample:

1. Representative samples
2. Samples designed to enhance anomalies related to particular mineral deposit types

Type 1 samples form the basis of regional geochemical mapping programs conducted by most national survey organizations. As the cost of occupying sample sites increases, however, consideration should be given to the collection of additional sample types. These can be analysed or stored in a sample library for selective re-analysis following the identification of areas considered to have the greatest potential for the discovery of economic ore deposits. Type 2 samples may be the most cost-effective for exploration for several types of ore deposits.

REPRESENTATIVE (STREAM SEDIMENT) SAMPLES - TYPE 1.

Active stream sediments, which comprise composite samples of weathering products, and have a limited Eh range because they are in contact with atmospheric oxygen (Garrels and Christ 1965) are the most representative sample type. These sediments have been used as a basis for geochemical mapping in areas ranging from tropical rain forest, through savannah and desert, to high mountain ranges and arctic regions (*see* Table 31.4). This type of sample

TABLE 31.4. SUMMARY DETAILS OF SOME STREAM SEDIMENT SURVEYS COVERING MORE THAN 5000 SQ. KM EACH.

Date	Country	Area	Sample Type(s)	Density	Analytical Method & Elements	Organization	Reference	Comments
1967-1968	Zambia	207000 1:8.5m, C, M	-80 mesh SS	1 p 190	AAS/Cu, Co, Ni, Pb, Zn, ES/Ag, Bi, Co, Cr, Cu, Fe, Ga, Mn, Mo, Ni, Pb, Sn, Sr, Ti, V, Zn	Imperial College App. Geochem. Res. Gp.	Armour-Brown and Nichol 1970	Central Zambia
1965-1973	Uganda	230000 1:2.0m, R	-80 mesh SS	1 p 200	ES/Be, Co, Cr, Cu, Mn, Mo, Nb, Ni, Pb, Sn, Sr, Color./Cu, Pb, W, Zn, Guiz./As	Geol. Surv. and Mines	Reedman 1973	Atlas produced
1969-1977	England and Wales	125000 1:2.0m, R, M	-80 mesh SS	1 p 2.5	ES/Al, Ba, Co, Cr, Cu, Fe, Ga, K, Li, Mg, Mn, Ni, Pb, Sc, Si, Sr, Ti, V AAS/Zn, Cd, Color./Mo, Guiz./As	Imperial College, App. Geochem. Res. Gp.	Webb <i>et al.</i> 1978	Atlas produced
1969-1979	Swaziland	17400 1:0.25m, C	-80 mesh SS; PC	1 p 2-4 SS 1 p 50 PC	AAS/Cu, Pb, Zn, Mn, Co, Ni, Mo, Sn, XRF/As on SS. Semi-qu. XRF on PC	Geol. Surv. and Mines CIDA	Forgeron 1979	
1968-pres	Gr. Britain	230000 1:0.25m, P 1:0.75m, C	-100 mesh SS; PC	1 p 2 SS	ES/Ba, Be, Bi, B, Ca, Cr, Co, Cu, Fe, K, La, Pb, Li, Mg, Mn, Mo, Ni, Sr, Ti, U, V, Y, Zn, Zr	BGS	Plant and Moore 1979; Plant 1984	Scotland + part of N. England completed. 5 regional atlases pub.
1970-1973	Sierra Leone	23000 1:0.5m, A	-80 mesh SS	1 p 8	ES/Cu, Co, Cr, Pb, Ni, Mn, V	BGS/Geol. Surv. Dept.	Macfarlane <i>et al.</i> 1981	Northern Sierra Leone
1977-1973	N. Ireland	12400 1:0.63m, C, M	-80 mesh SS	1 p 2.6	ES/Al, Ba, Ca, Co, Cr, Cu, Fe, Ga, K, Mg, Mn, Ni, Pb, Sc, Si, Sr, V, Zn Guiz./As. Color./Mo	Imperial College, App. Geochem. Res. Gp.	Webb <i>et al.</i> 1973	Atlas produced
1973-1974	Sweden	8000 1:0.05m, P	Organic SS	1 p 0.8	XRF/Y, U, Th, Zr, Zn, Rb, W, ES/Cu, Pb, Zn, Mo, Co, Mn, Fe, Ni, Mg, V, Ti, Ca, Ba, Sr, Ag, Bi, As, Sn, Be, Cr	Geological Survey	Larsson 1976	Other areas covered
1977-1975	Republic of South Africa	12000 1:0.25m, P, R	-200 mesh SS	1 p 1	AAS/Cu, Pb, Zn, Ni, Cr, Co, Mn ES/Ce, Nb, XRF/P, Mo, As, W, Th, U Later XRF/20 elements	Geological Survey	Beeson <i>et al.</i> 1978	Part of a larger prog. (see also Frick and Strauss 1987)
1974-1980	Italy	10000 P, M	-80 mesh SS	1 p 1.8	XRF+AAS/Cu, Pb, Zn, Hg, Fe, Mn, As, W, Mo, Sn, Be	Ist. di Geol. Geof. RIMIN SpA	De Vivo <i>et al.</i> 1984	Calabria region
1975-1980	Australia	6000 1:0.1m, ?P M, A	-80 mesh SS	1 p 2/3	AAS/Be, Co, Cr, Cu, Fe, Li, Mn, Ni, Zn, XRF/As, Ba, Bi, Ce, F, Mo, Nb, Pb, Rb, S, Sn, Th, Ti, U, W, Y	Bur. Min. Resources	Chork & Cruikshank 1984	Siegal + Hedleys Creek areas, NT/ Qund border

TABLE 31.4. CONTINUED.

Date	Country	Area	Sample Type(s)	Density	Analytical Method & Elements	Organization	Reference	Comments
1977-1977	France	790000	SS	2-4 p 1	ICP/22 elements + AAS/Au	BRGM	Wilhelm <i>et al.</i> 1987	Prot./palaeozoic areas
1977-1977	USSR	600000 1:0.05m- 1:1m, ?P, M	Silt fraction SS	1 p 1 and 1 p 6	???/Ag, Mn, Ba, P, Ni, Co, V, Pb, Zn, ?	Inst. Geochemistry, Irkutsk.	Filippova <i>et al.</i> 1983	Siberian plat-form area
1976-1986	Canada B. Columbia Yukon	450000 1:1m, 1:2m R	-80 mesh SS	1 p 13	Various/U, Zn, Cu, Pb, Ni, Co, Mn, Fe, Mo. Some samples for Hg, Ag, As, V, F, W, Sn, Ba	Geol. Surv. Canada	Lund 1987	Nat. Geochem. Rec. Series. Also other areas. Prov. Survs involved.
1975-1979	Alaska, USA	380000 1:6m, R, M	-100 mesh SS	1 p 10	NAA/Al, Ba, Ca, Dy, Mg, K, Na, Sr, Ti, U, V, Sb, Ce, Cs, Cr, Co, Eu, Au, Hf, Fe, La, Lu, Sc, Ta, Tb, Y, Zn XRF/As, Bi, Cu, Pb, Ni, Ag, Sn, W, Zr	Los Alamos Nat. Laboratory, N.M.	Weaver <i>et al.</i> 1983 Bolivar <i>et al.</i> 1987	Li, Be on some samples, Atlas produced. Part of US Dep. Ener. Nat. Ur. Res. Ev. (NURE) prog.
1975-1979	Ecuador	6000	-60 mesh SS	1 p 5	AAS/Cu, Co, Pb, Zn, Ni, Fe, Mn Guiz./As, Color./Mo.	BGS/Direccion Gen. Geol. Minas	Aucott <i>et al.</i> 1979	
1975-1980	Indonesia	190000 1:1.5m, P, R	-80 mesh SS	1 p 10	AAS/Cu, Co, Pb, Zn, Ni, Fe, Mn, Ag, Li, K, Cr, Color./Sn, Mo, V, W Guiz./As	BGS/Directorate of Mineral Resources	Page <i>et al.</i> 1978 Page and Young 1981 Stephenson <i>et al.</i> 1982	N. Sumatra, atlas produced
1976-1979	Burma	9430 1:0.25m, A	-80 mesh SS	1 p 2.5 - 1 p 10	AAS/Cu, Pb, Zn	BGS/Dept. Geol. Surv. and Min. Exp.	Amos <i>et al.</i> 1981	Some areas sampled at lower density
1976-1982	Solomon Isl.	8600 1:0.05m, P, A 1:0.1m, P, A 1:0.2m, A	-80 mesh SS	>1 p 1	AAS/Cu, Co, Pb, Zn, Ni, Ag, Mn	BGS/Geology Div. Min. Nat. Resources	Dunkley 1986 Ridgway and Coulson 1987	Choiseul + New Georgia, Western Solomons
1976-1983	Bolivia	130000 1:1m, P 1:4m, R	-100 mesh SS	1 p 16	AAS/Ag, As, Co, Cu, Fe, Mn, Pb, Zn ES/B, Ba, Be, Cr, La, Li, Mo, Nb, Sn, Sr, Y, Zr	BGS/GEOBOL	Appleton and Llanos-Llanos 1985	Eastern Bolivia, atlas produced
1976-1982	French Guiana	18000 P, R, M, A	-120 mesh SS	~1 p 1	ES/Mn, P, Ti, Li, B, V, Cr, Co, Ni, Cu, Zn, As, Sr, Y, Nb, Mo, Zr, Ag, Cd, Sn, Ba, La, W, Pb, Bi, Sb. +majors	BRGM	Zeegers 1979 Lasserre <i>et al.</i> 1987	Not continuous areal coverage

TABLE 31.4. CONTINUED.

Date	Country	Area	Sample Type(s)	Density	Analytical Method & Elements	Organization	Reference	Comments
1977-1983	Malaysia	31000 1:0.25m, P, C. 1:0.13m, P 1:0.06m, P	-80 mesh SS, -150 mesh PC	1 p 1.5 SS ? 1 p 10 PC	AAS/Cu, Mo, Zn, Ag, Co, Ni, Fe, Mn, Hg, Color./W, As, Sn, Fluor./U, Au instead of Hg in PC	Geological Survey of Malaysia/CIDA	Chu <i>et al.</i> 1984	Central penin- sular Malaysia
1977-1983	Federal Republic of Germany	210000 1:2m, R	-80 mesh SS	1 p 3	AAS/Pb, Zn, Cd, Cu, Ni, Co, Li, Sn, ES/Ba, Cr, Sr, V, Color./W, Fluor./U, SIE./F	Fed. Geol. Survey	Siewers and Fauth 1983, Fauth <i>et al.</i> 1985	Atlas produced
1978-pres	P. Rep. China	?000000s 1:0.2m	SS	? p ?	XRF/ICP/AAS/SIE/Color./+other Ag, Au, Hg, As, B, Bi, Be, Cd, La, Li, Mn, Mo, Nb, Ni, P, Pb, Sb, Sn, Sr, Th, Ti, U, V, W, Y, Zn, Zr + majors	Inst. Geophys. Geochem. Explor., MGMR.	Xie <i>et al.</i> 1986	Reg. Geochem. National Rec. Proj. (RGNR). Prov. and Nat. atlases to be published
1979-1980	Greenland	14000 R	-100 mic SS	1 p 6	XRF/K, Ca, Ti, Cr, Mn, Fe, Ni, Cu, Z, Ga, Pb, Sr, Rb, Y, Zr, Nb, Mo NAA/U	Geological Survey of Greenland	Armour-Brown and Olesen 1984	South Green- land. Other areas covered (see Steenfelt, 1987)
1979-1981	Peru	6300 1:0.25m, A	-80 mesh SS	1 p 6	AAS/Cu, Co, Pb, Zn, Ni, Ag, Mn Color./Mo	BGS/Direccion de Geologia Minera	Bennett <i>et al.</i> 1981	
1977-1977	USA	170000 R	-100 mesh SS	1 p 10	NAA/Al, Au, Ba, Ca, Ce, Cl, Co, Cr, Cs, Dy, Eu, Fe, Hf, K, La, Lu, Mg, Mn, Na, Rb, Sb, Sc, Sm, Sr, Ta, Tb, Th, Ti, U, V, Yb, Zn, XRF/Ag, Bi, Cu, Nb, Ni, Pb, Sn, W, Cd, As, Zr, ES/Be, Li	Los Alamos National Laboratory	Bolivar 1986	Colorado, part of US Dep. Ener. Nat. Ur. Res. Ev. (NURE) prog. Also other areas (see Ferguson and Price 1976)
1979-1982	USA	23300 C	-60 mesh SS and HM	1 p 3.3 SS ~1 p 8 HM	ES/Ag, As, Au, Ba, Be, Bi, Ca, Cd, Co, Cr, Cu, Fe, La, Mg, Mn, Mo, Nb, Ni, Pb, Sb, Se, Sn, Sr, Th, Ti, U, V, W, Y, Zn, Zr	USGS	Nowlan <i>et al.</i> 1987	Parts of Maine, Vermont and New Hamp- shire. Part of US Min. Ass. Prog.
1987-1987	Belgium	12000 1:0.1m, P, A	-80 mesh SS	1 p 1	ICP/20 elements	Univ. Louvain	Sondag 1983	Ardenne: region
1987-1987	Spain	????	-80 mesh SS	2 p 1(pre 1983 prg)	AAS/Pb, Zn, Cu, Ni, Co, Fe, Mn, Ag, Cd, As, Sb, Hg	Geol. Surv. Catalonia Univ. Barcelona	Font <i>et al.</i> 1983	5 yr. prog. Catalonian coastal ranges

TABLE 31.4. CONTINUED.

Date	Country	Area	Sample Type(s)	Density	Analytical Method & Elements	Organization	Reference	Comments
1978-1977	Austria	42000 1:0.05m, P 1:1m, R, ?M	-80 mesh SS	1 p 1.4	ICP/XRF/AAS/ES/Gutzeit for 35 elements	Geological Survey Voest-Alpine AG. Joanneum Res. Soc.	Hausberger <i>et al.</i> 1987; Kurz 1987	Central Alps and Bohemian Massif. Atlas to be produced
1981-1986	Kenya	50000 1:0.25m, P, A	-80 mesh SS, PC	SS 1 p 5-8 PC 1 p 15	AAS/Cu, Co, Pb, Zn, Ni, Mn, Fe, Ba, Sr, Li, Fluor. / U on SS. XRF/Ti, Fe, Mn, As, Ba, Co, Cr, Cu, La, Mo, Ni, Nb, Pb, Sn, Sr, Th, U, V, W, Zn, Zr on PC	BGS/Mines and Geol. Department	Ridgway in Hackman <i>et al.</i> ; Hackman; and Charsley, all in press; and Key, 1987	
1982-1986	Zimbabwe	8860, NE 4400, H 1:0.1m, P, A	-80 mesh SS	>1 p 1NE 1 p 2.7H	AAS/Cu, Co, Pb, Zn, Ni, Mn, Li XRF/Sn, W, Ta, Ba, As, Zr, Ti	BGS/Geol. Surv. Dept. b, c	Dunkley 1987a, b, c	Harare (H) and North East (NE). Makaha (860) sampled at 3.8 p 1.
1982-1977	Sweden	????? R	Organic SS	? p ?	XRF/Na, K, Mg, Al, Si, Ti, Fe, Mn, S, P, Cu, Pb, Zn, Ni, Cr, Co, Mo, Rb, Sr, Y, U, Zr, Nb, NAA/Se, Cd, As, Hg, Au	Geological Survey	Ek 1987	Nationwide survey
1987-1987	Czechoslov. Bohemian Mas.	42000 1:0.05m 1:0.2m	-80 mesh SS -200 mesh SS	0.95 p 1	AAS/Cu, Pb, Zn, Ni, Mn on -80m ES/Cu, Pb, Zn, Ni, Ag, As, Bi, Co, Mo, Sb, Sn, Li, B, Be, V, W on -200m	Geological Survey	Barnet and Duris 1983	
1987-1987	Canada Nova Scotia	8000 1:0.05m, A, M	-80 mesh SS	1 p 2.5	?/Cu, Pb, Zn, Ag, Fe, Mn, Ni, Co, As Hg, U, Mo	Nova Scotia Dept. Mines + Energy	Rogers <i>et al.</i> 1987	Catchment basin maps produced
1980-1986	Finland, Norway Sweden	250000 1:4m, P, M, A	Fine fract SS; HM	1 p 34	ES, XRF, NAA for 30 elements	Geol. Surv. Finland Norway, Sweden	Bolviken <i>et al.</i> 1987 Bergstrom <i>et al.</i> 1987	Fennoscandia N of 66N Nordkalott Project. Atlas to be produced
?1983	Saudi Arabia	10500 A, M	PC	1 p 9	ES/Fe, Mg, Ca, Ti, Mn, Ag, As, Au, B, Ba, Be, Bi, Cd, Co, Cr, Cu, La, Mo, Nb, Ni, Pb, Sb, Se, Sn, Sr, V, W, Y, Zn, Zr	USGS	Raines and Allen 1985	

AREA = area in sq. km. followed by map scale and type: C contoured, P - point source, R - cell, raster, pixel etc., M - multielement, factor score etc., A - anomaly.
 SAMPLE TYPE: SS - stream sediments, PC - pan concentrates, HM - heavy mineral. DENSITY = number of samples per sq. km. ANALYTICAL METHOD: AAS - atomic
 absorption spectroscopy, ES - emission spectrograph, ICP - inductively coupled plasma emission spectroscopy, XRF - X-ray fluorescence spectroscopy, NAA - neutron acti-
 vation analysis, SIE - specific ion electrode, Gutz. - Gutzeit method, Color - colorimetry, Fluor. - fluorimetry, ? - Sufficient information not available.

is particularly important in geochemical mapping where petrogenetic elements are included in the program, as in the case of the NURE, CUSMAP and other resource analysis programs in the U.S.A., the regional geochemical programs conducted by the BGS in Britain, the GSC in Canada, the BRGM in France and North Africa, and the Nordkalott Project in the Scandinavian countries. Such maps form the primary geochemical data sets for integration with geological, satellite imaged, and geophysical data sets or mineral deposit modeling and resource assessment studies.

The main requirement for stream sediment samples is that representative sampling and sub-sampling procedures are used at all stages of sample collection and reduction and that the methods are appropriate to the analytical techniques to be employed. It is then possible to obtain extremely reproducible data (*see* next section) and to prepare maps giving point source data for individual sample sites. This is preferred to an approach whereby large sampling/analytical errors are generated requiring smoothing of data to produce only generalized maps. Where stream sediments contain an important detrital component, for example in higher latitudes, field sieving should be employed to ensure that adequate quantities of the appropriate size fraction (frequently -80 to -100 BSI Mesh (+177 μm to -152 μm); Table 31.4) are collected. Slurry screening using the minimum of water ensures that the fine and colloidal fractions are recovered while achieving more quantitative separation of the fine fraction than is the case when sieving is carried out on previously dried samples. The necessity of sieving large volumes of sediment to obtain representative sub-samples has been shown to be particularly important for Au exploration (Day and Fletcher 1987). Freeze-drying, which produces a friable, easily split sample can be used to improve representative sub-sampling and is essential if volatile species such as Hg, As, and Se are to be determined.

The optimum size fraction of stream sediments may vary in different environments with a generally coarse upper screen required at high latitudes and altitudes, and special sampling devices designed to recover the fine fraction in suspension needed in areas of particularly high altitude such as British Columbia (Levinson 1974). Organic stream samples have been widely employed in northern Scandinavia where normal sedimentary material may be lacking for long distances in the stream channels (Larsson 1976; Bolviken *et al.* 1987). In arid and semiarid terrains an ultrafine or coarse fraction may be most suitable since intermediate fractions may comprise mainly barren siliceous material. Beeson *et al.* (1978) chose the -200 mesh (-76 μm) fraction because it gave fewer analytical values below the detection limit for the majority of elements; and the element populations thus approximated more closely a normal distribution. Mazzuchelli (1980) also de-

scribed the use of -200 mesh (-76 μm) sediment in the Warburton Range, Western Australia; while Moeskops and White (1980) found that the +35 to -18 mesh (+500 μm to -1 mm) fraction was the optimum sampling mesh in South Australia; and Skey and Young (1980) reported the use of the -20 mesh (-840 μm) fraction at the Que River Zn-Pb deposits in Tasmania. Similarly, Bugrov (1974) described the use of +60 to -18 mesh (+250 μm to -1 mm) material in the Eastern Desert of Egypt as a means of overcoming problems associated with the presence of fine aeolian sand and Zeegers *et al.* (1985) recommended the use of the +250 mesh (+62 μm) fraction. None of the Australian surveys, however, were designed for the preparation of multielement regional geochemical maps.

The scale of regional geochemical mapping can be such that different climatic regimes are covered over a period of several years. This raises difficulties in maintaining compatible representative sampling because of the possibility of climate-related temporal variations in the chemistry of the stream sediments. In temperate zones such variations have been considered insignificant (Barr and Hawkes 1963; Bolkiven *et al.* 1979; Chork 1977), but in regions with pronounced climatic fluctuations, important temporal changes in trace element concentrations have been noted (Govett 1961; De Grys 1962; Ishack and Dunlop 1985; Steenfelt 1987). Recent work in Zimbabwe and the Solomon Islands has shown that changes in stream sediment chemistry are not strictly seasonal in nature but are related to longer-term climatic cycles or catastrophic flooding events. In the seasonally wet/dry tropics for example, samples collected during one dry season may not contain the same trace element levels as those taken from the same sites during the next dry season. In the humid tropics, the passage of a cyclone can lead to a marked alteration in the chemistry of stream sediments. The changes affect petrogenic elements such as Ba, Rb, Sr, and Ti as well as ore-forming ones. In the Solomon Islands, for example, the passage of the tail of a cyclone caused differences of 0.7 percent in Ti and over 250 ppm in Sr in the sediments from a stream on Guadalcanal, while in Zimbabwe a fall in Pb from over 200 ppm to less than 60 ppm was recorded over three successive dry seasons near a mineralized vein (Ridgway 1987). Some form of standardization of data is needed and regular sampling of selected reference stations throughout the area to be mapped as a means of monitoring and adjusting data is preferred (Ek 1987).

Sample densities vary considerably, but more than 60 percent of those indicated in Table 31.4 used a density greater than 1 per 5 km² with most using densities greater than 1 per 3 km². The two programs with the lowest sample density (1 per 190 and 1 per 200 km²) were among the earliest and there appears to be a general trend now toward the

production of high density, multielement surveys aimed at the production of geochemical maps (Govett 1986), although the Nordkalott Project used a density of 1 sample per 30 km². Whatever the sampling density employed, emphasis is now on the collection of high precision data rather than the generation of large amounts of imprecise data requiring smoothing or other statistical manipulation. Stream sediment sampling is generally precluded in areas where the surface drainage is dominated by lakes and in karst areas, and is generally replaced by lake sediment (Allan *et al.* 1973) and soil sampling respectively. Stream sediment sampling is also of limited value in areas of heavy metal contamination. However, in such circumstances overbank (Otteson 1987) and deep soil sampling may be used instead. Efforts to find methods of integrating the data obtained using these samples with those obtained using stream sediment samples are required particularly if continental or world geochemical atlases are to be prepared.

In some cases it is desirable to supplement stream sediment sampling with water sampling, particularly in arid terrains where buried ore deposits are sought (Giblin, in press) and for uranium exploration generally where the levels of dissolved carbonate are high. In low-lying arid terrain, the long residence time, the high salinity, and low organic content of surface waters and the relatively stable flow regime mean that the trace element contents may be well above the analytical limit of detection of several multielement methods. However, a sound knowledge of mineral equilibria in aqueous systems is required for data interpretation (Langmuir 1978; Giblin, in press).

In regimes characterized by large climatic variations, or where the proportion of ground and surface water fluctuates, the concentrations of trace elements in surface water may be too variable for geochemical mapping. Moreover, the difficulty in removing suspended organic and other colloids may cause serious analytical difficulties. Nevertheless, the systematic determination of U and Zn in surface waters to identify uranium and base-metal deposits, and of pH, total dissolved carbonate, and total conductivity determinations for interpretative purposes, have been shown to be useful in Greenland and in Britain. Where levels of total dissolved carbonate or P are high, U determinations in water are preferred to those made on stream sediment samples, which may fail to show anomalies even where they are collected directly over U mineralization (Dyck 1975; Institute of Geological Sciences 1978).

SAMPLES DESIGNED TO ENHANCE ANOMALIES — TYPE 2

Ore deposits by their nature contain high concentrations of elements in ore rather than rock-forming mineral phases. Special sampling media can be used

to take advantage of the different physical or chemical properties of such minerals relative to common, predominantly silicate, rock-forming minerals. Heavy mineral concentrates, which are aimed at improving contrast for elements held in resistate mineral phases, have been shown to be of value, for example in exploration for scheelite mineralization in Spain (Turiel *et al.* 1987) and barite mineralization in Scotland (Coats *et al.* 1981). They are particularly useful in exploration for elements that are of high value and low average concentration, and which occur in discrete heavy mineral grains, including the platinum group metals (PGMs) and sometimes Au. Heavy mineral concentrates have also been demonstrated to be the most sensitive sample type for the identification of epigenetic Au mineralization in the Pacific Cordillera of Alaska (Sutley *et al.* 1987). They may also be useful in concentrating iron pans and ironstones enriched in trace elements, and have been found to be effective in laterite and arid terrains (Mazzuchelli 1986, in press).

Martin *et al.* (1984) have shown that separation and analysis of the weakly magnetic, secondary iron oxide constituents of stream sediments yield longer anomalous dispersion trains and improved anomaly contrast for several ore elements. These patterns may have a similar origin to those in ultrafine stream sediments coatings (Chao and Theobald 1976) and colloids, which adsorb and concentrate elements from minerals that are preferentially leached, including sulphides, and so constitute a useful sample medium (Carpenter *et al.* 1975; Nowlan 1976; Whitney 1981; Hale *et al.* 1984).

Precision and sensitivity are less important in sampling and analysis based on Type 2 samples than for Type 1 samples. Moreover, Type 2 samples are generally less suitable for multi-purpose geochemical mapping because petrogenetic elements are not included. Other difficulties in the use of Type 2 samples for multi-purpose geochemical mapping include the variability of heavy mineral concentrates in relation to geomorphological factors and individual sampling skills; although errors attributable to varying sample volumes and personnel with different panning skills can be reduced by standardizing procedures at each site or by the use of a sluice box (Brundin and Bergstrom 1977). In the case of colloids, large numbers of false anomalies can be generated which reflect complexation and adsorption in the surface environment, rather than the concentration of elements in bedrock. On the other hand, mineral exploration, particularly for certain elements such as Au and its pathfinders, may more profitably be performed using Type 2 samples since the average level of Au in stream sediments is commonly below the detection limit of most of the analytical techniques used for geochemical mapping. Heavy mineral concentrates are of value in detecting Au where it occurs in +80 mesh (+166 μ m) particles, while epithermal Au deposits and mineralization at low

latitudes may be better detected by the use of colloids or ultrafine stream sediment samples (Nichol 1986). Ideally, surveys should include Type 2 samples in addition to samples collected for geochemical mapping. For example, Watters (1983) has shown that in Sri Lanka, heavy mineral concentrates complement data obtained using fine mesh stream sediment samples; Zn anomalies in the two media show relatively little correspondance.

ANALYTICAL METHODS

A review of some of the analytical methods suitable for exploration geochemistry is given in Fletcher (1981) and only a brief summary is presented here. As in the case of sampling methods, the choice of analytical procedure depends on the aims and objectives of the regional geochemistry program.

For geochemical mapping where petrogenetic elements are to be determined in addition to ore and pathfinder elements, determination of the "total" concentration of a range of elements in a representative sub-sample is required. This can best be achieved by the analysis of a fused or powdered sub-sample using one of three instrumental methods: atomic emission spectrometry (ES), wavelength dispersive X-ray fluorescence (XRF) and instrumental neutron activation analysis (INAA). The application, advantages and limitations of these techniques, which are generally suited to different suites of elements (Table 31.5), are discussed in detail in Fletcher (1981), Croft (1986), and Potts (1987).

On the other hand, acid dissolution and selective extraction methods may help to enhance geochemical anomalies for ore elements which are in

secondary minerals, or are weakly bound on colloids or coatings. These methods are routinely used in mineral exploration with instrumental determinations being carried out by atomic absorption spectrophotometry (AAS) or inductively coupled plasma atomic emission spectrometry (ICP-ES). An ICP source linked to a mass spectrometer (ICP-MS) holds promise as a technique for geochemical mapping.

The longest established of the methods is DC arc source ES, which is most suitable for light and transition elements and some major rock-forming elements. The method is sensitive but it has marked upper detection limits, variable from element to element, which make it better suited to geochemical mapping than to mineral exploration. However, the increasing importance of boron and the light elements as pathfinder elements for gold and base metal mineralization means that it is increasingly used to complement data prepared for mineral exploration using other methods. The technique is particularly appropriate for national survey organizations preparing geological maps and is used, for example, by the BGS in the Regional Geochemical Mapping Program of the U.K. and by Scandinavian countries for the Nordkalott Project (Table 31.4). Many of the difficulties of maintaining precision, and of long-term drift which in the past made the technique highly dependent on operator skill and experience have been overcome by the use of computer control systems in the latest generation of machine. Fine grinding of samples and the use of a long burn time of material previously ignited at 450 degrees C further improves precision and eliminates interference from organic material and carbonate. It is essential, however, that such instruments be ade-

TABLE 31.5. PRINCIPAL ELEMENTS OF INTEREST IN REGIONAL GEOCHEMISTRY AND A GUIDE TO THEIR SIMULTANEOUS INSTRUMENTAL DETERMINATION.

Elements of Interest	Instrumental Method		
	ES	XRF	INAA
Li, Be, B	X		
Na, Mg, Al, Si, K, Ca	X	X	
Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn	X	X	
Ga, Ge, As, Se		x	X
Rb, Sr	X	X	X
Y, Zr, Nb	x	X	x
Ta, Hf			X
Pd, Ag, In			X
Sn	x	X	
Sb, Te			X
Ba, La	X	X	X
REE		x	X
W, Os, Ir, Pt, Au			X
Pb	x	x	
Th, U		x	X

X: Suitable method for most elements listed

x: Acceptable method, but with poor limits of detection for elements listed

quately calibrated using samples representative of the matrix occurring in the survey. For example, stream sediments and other surface samples may contain much higher levels of manganese and iron than rock samples and unrecorded interferences can seriously affect trace element determinations (Plant and Moore 1979).

The XRF method has a limit of detection down to a few ppm for most elements with atomic weights greater than fluorine, and it is particularly suited to the determination of the first and second row transition elements. Trace elements are normally determined in pressed pellets but major elements can also be determined accurately and precisely on samples fused in borate glass. The wide range of elements which can be determined and the relative ease of automation of XRF, which enables approximately 10 000 element determinations to be completed each week, makes it a particularly cost-effective tool for geochemical mapping. Moreover, the use of a larger sub-sample size than is the case in ES reduces sub-sampling error. The large dynamic range of the method makes it especially suitable for mineral exploration based on the analysis of heavy mineral concentrates.

The INAA method is most suitable for elements of intermediate to high atomic number and hence complements the range of elements which it is possible to determine using ES and XRF. In particular it is useful for the determination of Au and its pathfinder elements, the PGMs, W, U, Th, and the REE. The ability, depending on the reactor facility and cost, of analyzing samples ranging up to 500 g in size; the non-destructive nature; and matrix independence of the method make it particularly valuable for Au and PGM exploration based on heavy mineral concentrates. In addition, samples can be examined mineralogically following cooling after irradiation and analysis. The main limitations of INAA include: access to reactor facilities; the limited sensitivity for many important ore, pathfinder, and petrogenetic elements; the high cost, in some cases, of sample analysis; and the special requirements for storage of irradiated samples.

Of the instrumental techniques suitable for analysis of sub-samples in solution, AAS has been, and is likely to remain, one of the most commonly used methods, particularly where the principal objective of the survey is the detection of dispersion from mineral deposits and the enhancement of the associated anomalies. Dissolution of the sub-sample in a strong acid mixture (e.g. $\text{HF-HClO}_4\text{-HNO}_3$) dissolves most minerals, although some resistate oxides (e.g. cassiterite, chromite, beryl, ilmenite, rutile, spinel) and some sulphides may be incompletely dissolved (Langmyhr and Sveen 1965). Nebulization of the resulting leachate enables several base metals to be determined sequentially. The instrumentation is also sufficiently versatile to enable alternative analyte matrices, such as complexing

agents, to be used for the selective determination of adsorbed base metals, while organic solvents (e.g. methyl isobutylketone (MIBK)) can be nebulized for the determination of Au, and vapour can be introduced into the instrument for the determination of volatile species of, for example, As, Se, and Hg.

Selective leaching and analysis of the leachate by AAS can be used to determine the trace metals adsorbed by clay minerals (ammonium acetate leach), manganese oxides (hydroxylamine hydrochloride), iron oxides (ammonium oxalate) and/or by organic matter (hydrogen peroxide) singly or sequentially (Bolle *et al.*, in press). Although the selectivity of these leaches is imperfect, their use suppresses the geochemical response of detrital grains. This approach has been used with particular success in uranium exploration (Rose, in press). A special case of the use of selective leaching is the cyanidation of bulk stream sediment samples prior to gold analysis, which ensures that gold is extracted from an adequately large sample but eliminates the errors inherent in panning.

The ICP-ES method fulfils a similar role to AAS, but a wide range of elements can be determined simultaneously and the technique has increasingly replaced AAS over the last decade. Major and some trace element data suitable for regional geochemical mapping can be obtained if sample material is first fused with lithium metaborate to give a bead which is subsequently dissolved in acid for nebulization; but the high dilution factor which results limits the number of trace elements that can be detected. Direct dissolution of the sub-sample in a strong acid mixture (e.g. $\text{HF-HClO}_4\text{-HNO}_3$) provides an analyte in which most major metals (although usually not Au or U) can be detected. Although ICP-ES is generally less adaptable than AAS to different analyte matrices, it is particularly suitable for determinations on vapours: various combinations of As, Sb, Bi, Se, and Te can be determined simultaneously with considerable sensitivity by the introduction of their volatile hydrides into the ICP (Pahlavanpour *et al.* 1980a, 1980b; Walsh and Howie 1986).

The ICP-MS method is a method which has great potential significance for multielement geochemical analysis in the future (Gray and Date 1983). The method depends on an ICP source linked to a mass spectrometer. Date (1983) gives the many advantages of ICP-MS, which make it particularly attractive for analysis for regional geochemical mapping. The method can be used to determine a wide range of elements, from light elements such as Li, to heavy elements such as U, including the major elements, transition metals, the PGMs, Au, and its pathfinders. Limits of detection are typically an order of magnitude or more lower than with ICP-ES; consequently the limitations posed in ICP-ES by high dilution factors following sub-sample fusion and acid dissolution are greatly reduced or eliminated by

the use of ICP-MS. The instrument can be calibrated over at least four orders of magnitude, and its speed of operation, accuracy, precision, and freedom from matrix effects are comparable with those of ICP-ES.

Of the six main methods, most geochemical surveys (Table 31.4) continue to rely upon AAS and ES (or sometimes colorimetric techniques), reflecting the continued application of geochemical maps chiefly for the direct detection of geochemical anomalies related to mineralization. This is particularly the case in developing countries. Several recent geochemical surveys, such as those in the U.S.A., the U.K., France, and the Scandinavian countries, however, have also included a wide range of petrogenetic elements for geological mapping and metallogenic studies with determinations being made using quantitative INAA, XRF and DC arc ES methods.

DATA PROCESSING

Modern geochemical surveys can generate enormous quantities of data in a short period of time and the need for computers for data management at all levels of regional geochemistry is clear. Reviews of computer applications in sample planning, sampling, laboratory control, database management, and statistical analysis and mapping are given by Howarth (1983), Howarth and Martin (1979), Howarth and Garrett (1986), and Garrett (this volume).

Increasingly, the emphasis in data processing is on the preparation of precise high-resolution colour images and plots based on, for example, moving average (Green 1984) or universal kriging (Weaver *et al.* 1983) methods, which make it possible to study local geochemical features in detail and in the context of regional geochemical variation. Patterns and structures in the data can be readily identified using such images while the geochemist/exploration geologist can play a more direct role in data interpretation than by the use of mathematically based systems of identifying anomalies or outliers. Moreover the use of advanced computer-graphical techniques such as image analysis systems make it possible to analyse and integrate large numbers of multielement geochemical data sets interactively, and in relation to geophysical and satellite imaged data.

Different types of statistical analysis can also be performed on total or selected parts of images to prepare maps for exploration or resource analysis based on a combination of features from primary and/or derived images (Green 1984; Rogers *et al.* 1987; Greenbaum *et al.* 1986). Such an approach has been used successfully in a study in the east Midlands of England aimed at developing methods of exploration for buried ore deposits using basin analysis techniques more commonly used in hydrocarbon exploration. Prospectivity maps for "Pennine-style" (epigenetic fluoritic Mississippi Valley-

type) Pb-F-Zn-Ba mineralization were prepared using a combination of negative Bouguer gravity and heat flow anomalies (indicative of buried high heat production granites); together with seismic refraction and borehole data (to identify deep listric faulted sedimentary basins and platform limestone drapes over buried basement tilt blocks); "shadow" plots of aeromagnetic data and second derivative gravity maps (to indicate basement and near surface lineament systems); and geochemical data indicative of shale sequences containing an important trace element enriched organic/carbonate fraction. The approach, which was based on the preparation of metallogenic models to account for the known characteristics of Irish- and Pennine-style mineralization in Britain and Ireland as a basis for the development of exploration criteria, was shown to be considerably more powerful than the simple mathematical interaction of primary data sets (Hunting Geology and Geophysics 1983).

In Finland and Scotland, regional geochemical maps based on low-density sampling of basal tills and stream sediments respectively (Nordkalott Project 1986; Plant and Slater 1986), generally show similar relationships between geochemical and geophysical anomalies and belts of base metal mineral deposits and occurrences. In Finland, three marked linear features, which trend west to northwest and crosscut previously mapped geology, reveal a remarkable coincidence with the major sulphide occurrences. As in the Scottish Dalradian, the zones of rocks enriched in trace elements are also characterized by high specific gravity. The Finnish geochemical linears represent the continuation of "metalotects" such as the Pechenga Belt of the USSR. It has been suggested that such belts represent basins, characterized by lithospheric thinning and extension, and the rise of asthenosphere into the crust (Plant and Slater 1986), as proposed for the early phases of basin development generally by Jarvis and Mackenzie (1980). The anomalous geothermal gradient and tectonism favour ore genesis in such zones, which separate more stable areas of crust that tend to be barren of metals. The high density of the rocks in such belts might reflect the proportion of basic volcanics and volcanoclastic detritus and/or the subsequent deformation of the marginal basin sedimentary sequences against more stable rigid crustal blocks (Plant *et al.* 1984b).

Other ore deposit settings have characteristic geophysical anomalies. High heat production granites for example, although they can be represented by patterns for more than 30 chemical elements and geophysical characteristics, can be identified simply by their large negative gravity anomalies and high radioactivity (contents of U, Th, and K: Plate 31.1) (see Colour Folio near back of book). Deep listric-faulted sedimentary basins associated with Pb-Zn deposits can be identified using negative gravity anomalies, second vertical derivative gravity maps,

and seismic refraction data. At a more local scale, changes in the magnetic signature, particularly of volcanic rocks, can indicate the passage of sulphur enriched reducing or oxidizing ore fluids whereby magnetite is altered to pyrite or hematite respectively. For example, the magnetic signature of basalts is frequently obliterated around Archaean lode gold deposits where the Fe^{2+} /total Fe ratio may be as high as 0.92 compared to the average for basalts of 0.75 (Kerrick and Watson 1984). Regional geochemical surveys, in combination with geophysical or satellite imaged data, were used by Filippova *et al.* (1983) to identify fracture zones and major structures with diameters of 40 to 300 km on the Siberian Platform. These features are characterized by relatively high contents of Ag, Ba, and Mn; variations in P, Ni, Co, and V are controlled by stratigraphic and lithological units in the sedimentary cover.

Low-cost, microcomputer-based systems and service facilities are now making image analysis techniques more widely available and it is likely that exploration geochemists/geologists will increasingly be required to use such systems to screen data sets to identify exploration targets. The main difficulties are associated with the vast quantities of data being accumulated from different disciplines and sources. For example, SPOT satellite data is being added to the already large libraries of remotely sensed data while modern geochemical surveys commonly collect data for 30 to 40 chemical elements. It is also necessary to analyse such data in relation to 30 or 40 ore deposit types each of which has different geochemical, geophysical, and other signatures.

Mineral deposit models and systematic compilations of their attributes such as those published by the USGS; the Geological Survey of Canada, e.g. Eckstrand (1984); and the Geological Association of Canada, e.g. Morganti (1981); help to organize and rationalize exploration information, and a detailed exploration strategy has been developed for epithermal gold deposits (Adams 1985). Geochemical exploration models which anticipate the mechanism of dispersion, select appropriate sampling media, and estimate the nature and significance of anomalies in different surface environments, can also be formulated. A classification of models in tropically weathered terrains is described by Butt and Zeegers (in press). In general, however, such models and compilations lack input from systematic satellite imaged, geophysical, or geochemical data and exploration criteria have not been formulated for screening large spatially related data sets. Regional geochemistry has an important role to play in the formulation and compilation of mineral deposit models.

In the case of geochemical data, simple combinations of elements can be used as exploration criteria for most ore deposit types and there are several ways of representing trace element patterns which, in contrast to mathematical groupings, can be used

to deduce the chemical processes which have affected them. For example rare earth element (REE) abundances are usually normalized against chondrites. For other elements it is more appropriate to display their patterns normalized to estimates of the primitive mantle (Wood *et al.* 1979). Some elements are more useful than others in discriminating between tectonic environments, and procedures have evolved to use such elements in bi- or tri-element diagrams (see for instance, Pearce and Cann 1973; Floyd and Winchester 1978). Other bi-element plots using mobile/immobile element pairs and ratios have been applied to identify water/rock interaction (Plant *et al.* 1985).

Such plots can be prepared simply from regional geochemical exploration data held on image analysis systems using the methods described by Green (1984). The signature of stream sediment and rocks for high heat production metalliferous and barren granites in Scotland is shown in Figure 31.1, and of the barren Moine and the mineralized Dalradian late Proterozoic Precambrian sedimentary sequences in Figure 31.2 (Plant *et al.* 1984a, 1984b). In the north of England, combined images of Pb, Cu, and Ag can be used to identify plutonic and volcanic associated mineralization in the English Lake District and modified MVT mineralization in the northern Pennines (Plate 31.2). These methods of representing geochemical data could be more widely applied in geochemical exploration to constrain or develop mineral deposit models and to develop small subsets

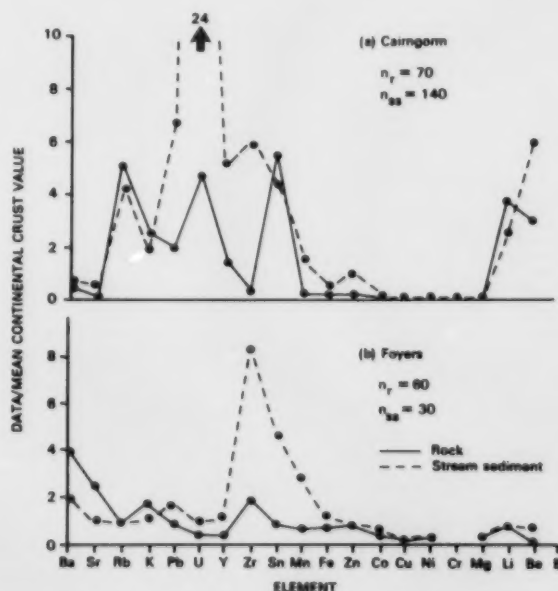


Figure 31.1. Mean element concentrations in rock and stream sediment, normalized to average crustal abundance, for the Foyers (barren) and Cairngorm (mineralized) granites (after Plant *et al.* 1984a).

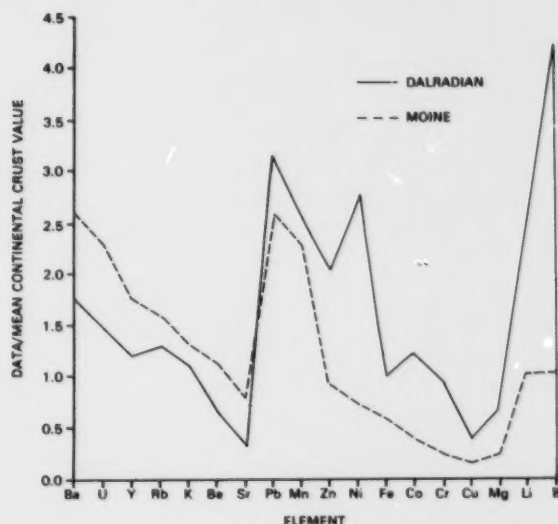


Figure 31.2. Mean element concentrations for stream sediments from the Moine (barren) and Dalradian (mineralized) sequences normalized to the mean continental crust values (Clark) (after Plant et al. 1984b).

of geochemically meaningful factors from initially large data sets.

Image analysis systems can thus be used to help to formulate metallogenic models and to test and develop powerful, robust, geochemical, geophysical, satellite imaged, and geological sets and subsets of exploration criteria.

Because of the large range of data available and the variability of the surface environment, the application of image analysis systems to the screening of geochemical and other data sets held in digital form, for different ore deposit types, would be greatly assisted by the availability of knowledge-based, or expert systems. Current systems, which include Classic, Piero (Ecole des Mines), Prospector (SRI/USGS), and Serge (BRGM), are generally regarded as experimental prototypes and they are not designed for screening spatially related data (Garrett and Leymarie, in press).

Considerable effort is required to ensure that high precision, regional geochemical maps and other data sets are available which can be used to develop and test such systems and to ensure that the geochemical signatures of different ore deposits in different surface environments are fully understood and documented.

CONCLUSIONS AND RECOMMENDATIONS

1. High-precision multielement geochemical data sets, which include petrogenetic elements, are prepared by national survey organizations in

many parts of the world for several purposes (e.g. environmental studies and as an aid to geological mapping) in addition to mineral exploration.

2. Such data sets can be used by the private sector to identify and follow up anomalies related to mineralization as dictated by short term economic cycles.
3. Representative sampling and rapid, quantitative, multielement analytical techniques are employed in the preparation of regional geochemical data sets, whereas methods designed to enhance anomalies for particular metals may be more appropriate for mineral exploration.
4. The use of colour raster graphical presentation, interactive data processing facilities based on PCs, and image analysis systems enables spatial patterns and structures in geochemical data to be readily identified. However, conventional point source and comparable data presentation methods still play an important role in detailed mineral exploration.
5. Regional geochemistry is an aid to, and extension of, geological mapping. In addition to defining anomalies directly related to mineralization, it provides information on metallogenesis in relation to tectono-magmatic and sedimentary processes. It can be used to identify major crustal lineaments, metallogenic provinces, and large volume source rocks.
6. Integration of regional geochemical with satellite imaged, geological, and geophysical data sets provides a powerful predictive tool in mineral exploration programs for both exposed and concealed ore deposits.
7. Regional geochemistry has a major role to play in formulating mineral deposit models and compiling their attributes. Such studies should be carried out in relation to models which anticipate the mechanisms of dispersion and the nature and significance of anomalies in different surface environments.
8. Identification of exploration targets will increasingly involve screening large numbers of multi-disciplinary data sets according to different ore deposit models and in a variety of terrains. Artificial intelligence systems may be of value in this task.

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32. Lake Sediment Geochemistry: Canadian Applications in the Eighties

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ABSTRACT

In the 1980s, advances in lake sediment geochemistry have been concentrated toward further development of field methods, preparation and analytical techniques, data interpretation and presentation, and an understanding of lake bottom characteristics. The most significant advances were in the study of the response of lake sediment and water to a number of different types of mineralization, principally gold, tin, tungsten, the rare earth elements, and the platinum group elements. New exploration applications in the 1980s for lake sediment geochemistry were a direct result of this work. During the 1980s there has been increased lake sediment survey coverage of Canada and increased application of these data for addressing environmental and public health concerns.

INTRODUCTION

Chemical, physical, and biological processes can interact within lakes to control the transport, accumulation, and fixation of elements into the sediments. Variations in the physicochemical-limnological conditions of a lake can effect the nature of the trace metal response of the sediments to mineralization, geographic-climatic, and geological environments. Descriptions of these processes and conditions and how they effect the mobilization, transport, and fixation of trace elements within a lake have been previously published, for example Coker *et al.* (1979), Cameron (1980, in press) and will not be discussed further.

Significant advances in the 1980s have been made in the understanding of glacial and post-glacial processes of lake formation by using acoustic subbottom profiling to map the glacial and lacustrine sediment facies (Shilts and Farrell 1982; Laroque 1985). The amount and nature of bottom fill could be of critical importance in evaluating the inflow effects of increasingly acid surface waters and groundwaters, expected to be generated by acid rain (Shilts and Farrell 1982).

Lake sediment geochemistry was originally developed for base-metal exploration where it continues to be used. In the 1970s, the use of lake sediment geochemistry for uranium exploration was

widespread and successful (Coker *et al.* 1979; Cameron, in press). The application of lake sediment geochemistry for gold, tin, tungsten, platinum group elements (PGE), and rare earth elements (REE) is the quest of the 1980s. The 1980s have also seen a dramatic increase in the lake sediment geochemical coverage of Canada, amounting to over 1 million km². The use of these data for addressing environmental and public health concerns has also been demonstrated (Coker and Shilts 1979; Fortescue 1985; Hornbrook *et al.* 1986).

This paper highlights some recent advances in acoustic subbottom profiling of lake basins, lake sediment geochemical survey coverage of Canada, and new applications for lake sediment surveys in mineral exploration.

LAKE BASINS

Maps drawn from the interpretations of acoustic subbottom profiles of lakes in the Canadian Shield can show the distribution and physical characteristics of modern-day lake sediments and unconsolidated sediments related to glacial processes (Klassen and Shilts 1982; Shilts and Farrell 1982; Shilts 1984; Larocque 1985). At Big Turkey Lake, Environment Canada's test site north of Sault Ste. Marie, subbottom characteristics (Figure 32.1) and the distribution of bottom sediments have been outlined by Shilts and Farrell (1982). Modern-day organic lake sediment or gyttja is not uniformly distributed throughout the lake, but is concentrated in thicker layers in the profundal basin where it constitutes an ideal sample site location. The sediment is usually greenish grey to brownish coloured with a variable organic content and consists of diatoms, pollen, algae, spore cases, and fibrous organic material all in a mush of organics and clay minerals frequently with oxides and hydroxides of Mn and Fe (Dunn 1980). Fluvial deltaic sands were found only at the south-east inlet of Big Turkey Lake but can also be found elsewhere in many other lakes. The gyttja may be underlain by till, proglacial laminated sediments, fluvial deltaic sand, or be in direct contact with bedrock. An acoustic subbottom profile of the lake (Figure 32.2) shows the shadow of deep bedrock depressions filled with glacial sediments, probably under proglacial conditions (Klassen and Shilts 1982). The whitish area, marked gyttja (see Figure 32.2), is the modern surface lake sediment. With this much clastic sediment within a lake basin and groundwater flow through these and adjacent clastic sediments at

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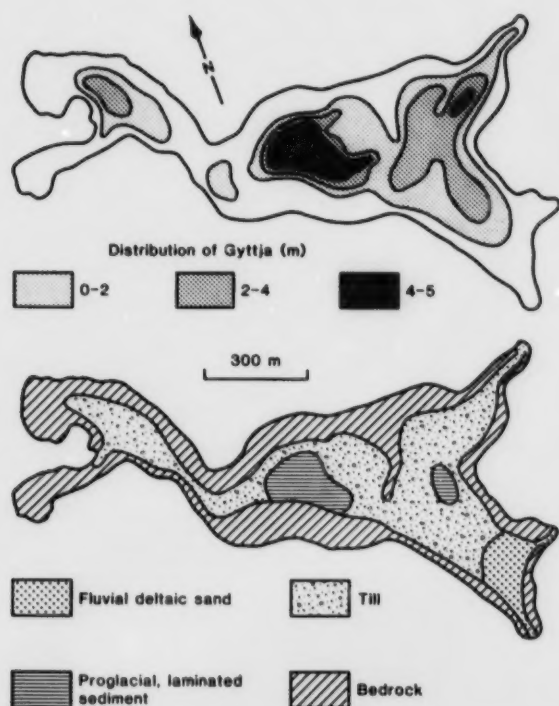


Figure 32.1. Thickness and distribution of modern-day lake sediments and the distribution of bedrock and glacial or proglacial sediments at Big Turkey Lake, Ontario (after Shilts and Farrell 1982).

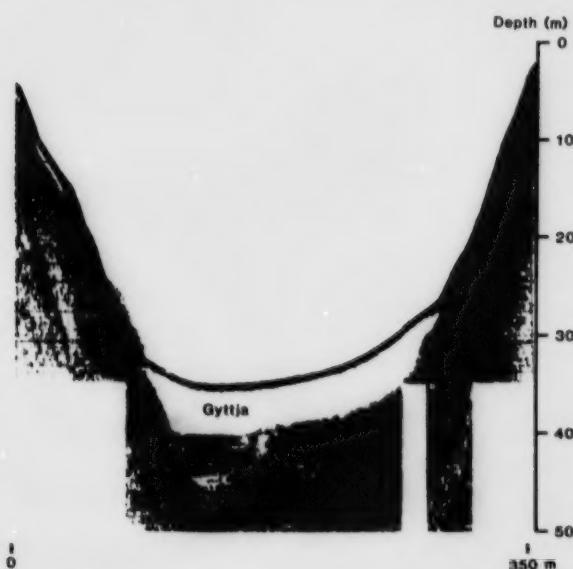


Figure 32.2. Acoustic subbottom profile across Big Turkey Lake, Ontario (after Klassen and Shilts 1982).

the surface, either of which may not be locally derived, the chemistry of the lake could be significantly influenced by their chemistry. This is dramatically evident where Paleozoic carbonate rocks from the Hudson Bay area have been glacially transported to the southwest and deposited on the granitic gneiss terrain along the north shore of Lake Superior, resulting in buffered alkaline lakes rather than the usual acidic lakes of the Canadian Shield (Figure 32.3) (Coker and Shilts 1979). It is necessary to understand the provenance and sediment characteristics of modern-day lake basins to know which factors play a dominant role that could effect the interpretation of lake sediment geochemical data.

REGIONAL GEOCHEMICAL SURVEYS

National Geochemical Reconnaissance (NGR) lake sediment surveys at the Geological Survey of Canada (GSC) began in the early 1970s (Hornbrook and Gleeson 1972; Davenport *et al.* 1974), expanded considerably under the Uranium Reconnaissance Program from 1975 to 1979 (Darnley *et al.* 1975) and after a slow period of a few years in the early 1980s were again nationally applied in 1984 under various Mineral Development Agreements with the Provinces.

These surveys, carried out by the Geological Survey of Canada, by the Provinces or jointly under various agreements, have covered significant areas of Canada (Figure 32.4) amounting to over 1.1 million km². The coverage of Canada by other types of NGR surveys totaling about 0.8 million km² is also shown in Figure 32.4. Some Cordilleran stream survey areas contain minor areas of lake surveys. Lake sediment coverage in Québec (Figure 32.5) (M. Beaumier, Geochemist, Ministère de l'Énergie et des Ressources (MER), Québec, personal communication, 1987) has been undertaken by the Provincial Ministry since 1983, generally at a sample density of 1 sample per 13 km². Other large surveys were carried out by the Sociétés de Développement de la Baie James (SDBJ) in 1973 and 1974, at an average density of 1 sample per 7 km², and by Soquem in 1976 and 1977 at an average density of 1 sample per 2 km².

The NGR lake sediment work in Canada is part of a national systematic methodology with specifications for collection, preparation, analysis, and publication, all of which are quality controlled. For 18 years, the Geological Survey of Canada has played the major role in developing the technology and carrying out NGR survey programs to provide a systematic high-quality geochemical data base across Canada.

The data base is used by industry for mineral exploration, by governments for assessment of resources, and as an aid to geological mapping. It is also relevant to environmental and public health programs.

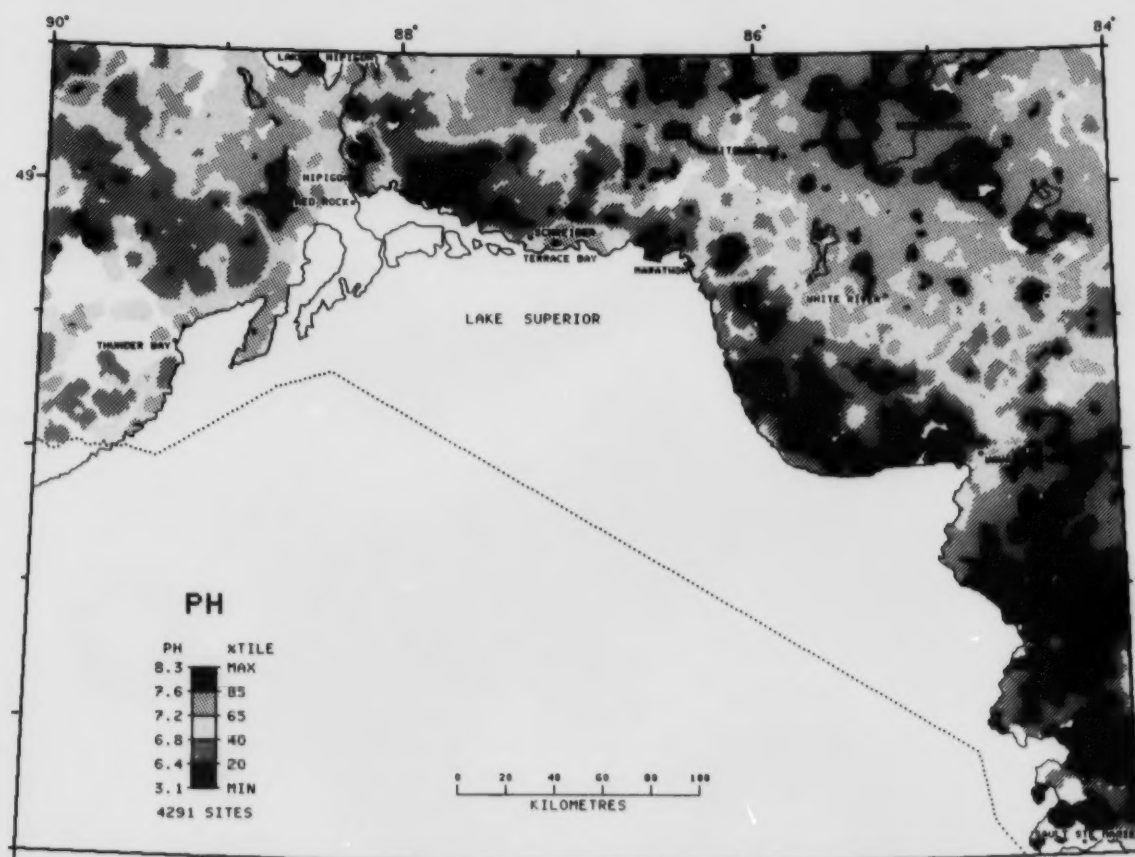


Figure 32.3. Distribution of acid to alkaline lakes based on lake water pH, north shore Lake Superior, Ontario (after Coker and Shilts 1979).

NEW EXPLORATION APPLICATIONS

TIN

In 1985, the effectiveness of using lithophile elements in regional lake bottom sediment surveys was tested over the East Kemptville tin deposit area of Nova Scotia (Rogers and MacDonald 1985; Rogers and Garrett 1987). The deposit is located on a topographic high of granitoid rocks surrounded by low-lying till plains on which most of the regions' lakes have been developed. The tin mineralization, with traces of tungsten, is found in a greisen zone along the contact of the Davis Lake Granitoid Complex with metasedimentary rocks of the Meguma Group (Chatterjee and Strong 1984). A subset of 55 archived regional samples was selected from the deposit area and analyzed for Sn, Rb, F, and Cl. Anomalous values of Sn, Rb, and F were found to be related to the tin deposit and showed no relationship to the organic content (LOI) of the samples.

Following the preliminary test, a more comprehensive study was carried out using Sn, W, Au, U,

and other element data from 167 sites located in the tin deposit area. Anomalous Sn-bearing lakes (Figure 32.6), found in the major study, are radially distributed south, southeast, and southwest of the deposit. The W pattern (Figure 32.7) is similar but not as strong a regional anomaly as Sn (Rogers 1986). The less intense W anomalies may simply be a reflection of the less extensive wolframite mineralization. The radial down-ice pattern of Sn and W distribution has probably been controlled by topography, relief, and the polyphase glacial movements in the area (Stea and Grant 1982). The anomaly at South Horseshoe Lake (see Figures 32.6 and 32.7) indicates a translation distance of up to 17 km from the deposit. This significant distance of transport has almost certainly involved some glacial transport of Sn and W in the till. Evidence of mechanical transport in till is revealed at Moosefly Lake where the lake sediment was found to contain discrete grains of clean, sharp angular cassiterite in addition to numerous grains of zircon, monazite, and magnetite. Therefore, the 32 ppm Sn anomaly in Moosefly Lake is probably due to the presence of cassiterite

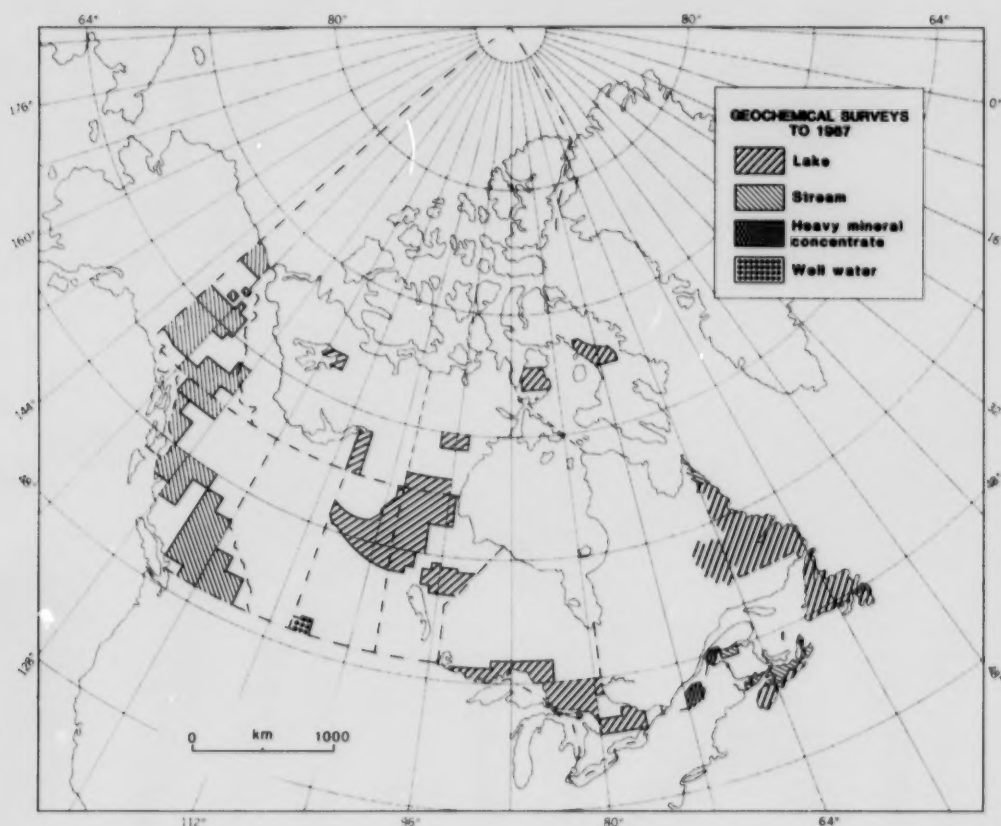


Figure 32.4. National Geochemical Reconnaissance (NGR) survey coverage of Canada, 1973 to 1987.

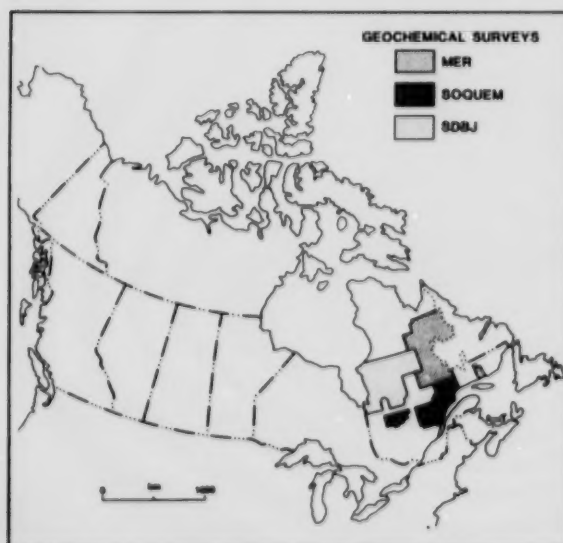


Figure 32.5. Lake sediment geochemical survey coverage of Québec, 1973 to 1987.

grains in the sample (Rogers and Garrett 1987). Further, the cassiterite grains in the Moosefly Lake sediment have a clean angular nature indicating minimal abrasion and waterborne transport. The cassiterite grains could have been moved from the deposit several kilometres to the immediate catchment basin of the lake by glacial transport. The common dispersal model of glacial clastic dispersion followed by hydromorphic dispersion into lake basins (Timperley and Allan 1974; Coker and Nichol 1975; Coker *et al.* 1979) must be reconsidered for lithophile elements present as refractory grains with more emphasis on mechanical dispersion. In contrast, for a test set of lake sediment samples collected from the tin-mineralized Ackley Granite area, Newfoundland, Davenport found no response for Sn (Davenport 1981).

TUNGSTEN

A good example of the effective use of W in lake sediment surveys was described by Davenport and Butler (1982, 1983). Their survey covered over 2000 km² of granitoid rocks in south-central Newfoundland defining several areas anomalous in W, particularly in the Granite-Meelpeag Lakes area

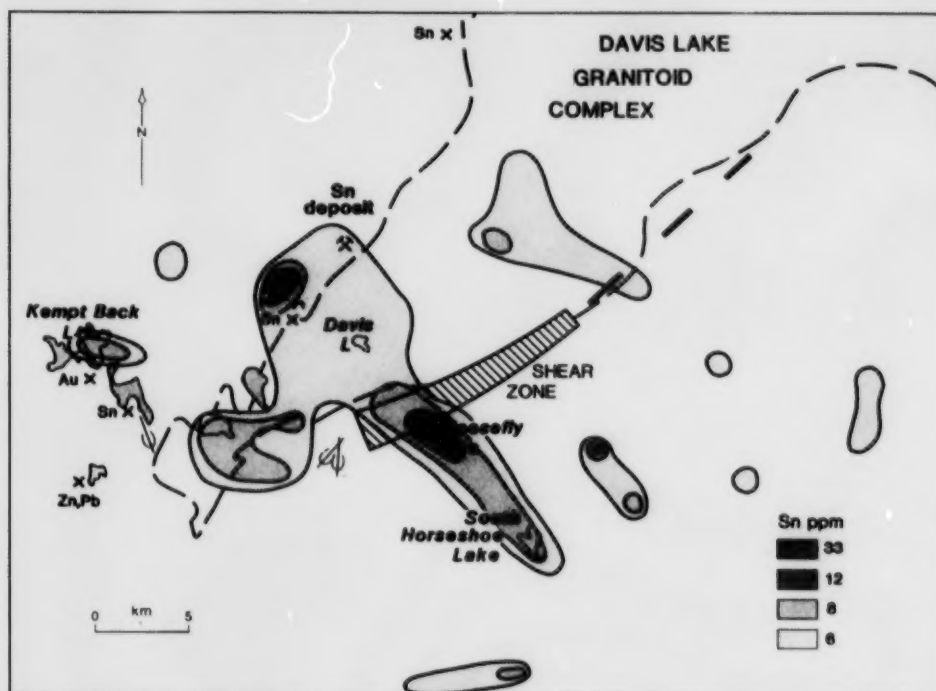


Figure 32.6. Distribution of Sn in lake sediments; East Kemptville tin deposit area, Nova Scotia (modified after Rogers 1986).

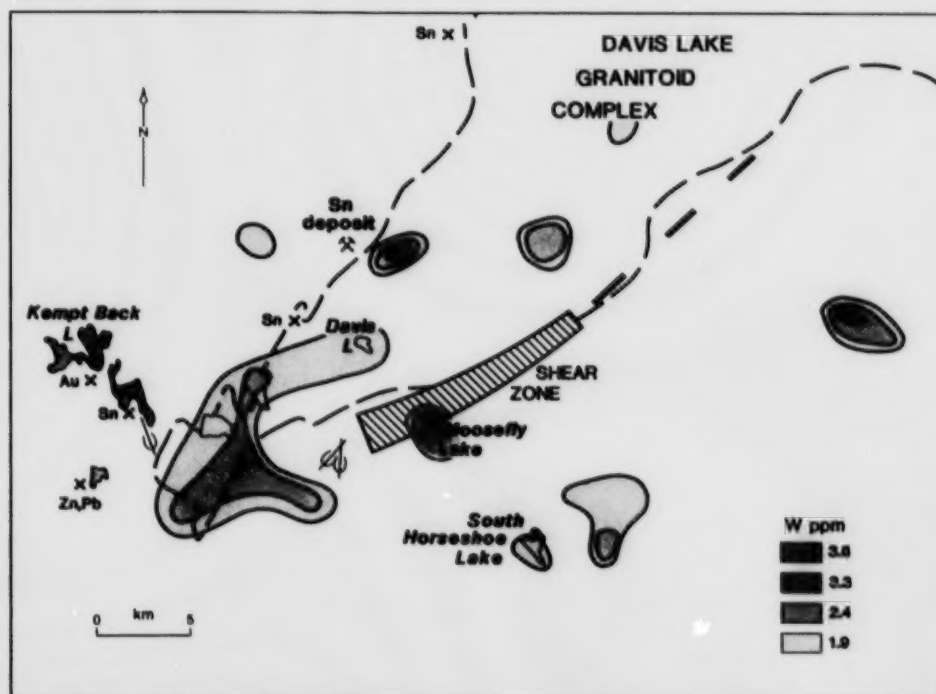


Figure 32.7. Distribution of W in lake sediments; East Kemptville tin deposit area, Nova Scotia (modified after Rogers 1986).

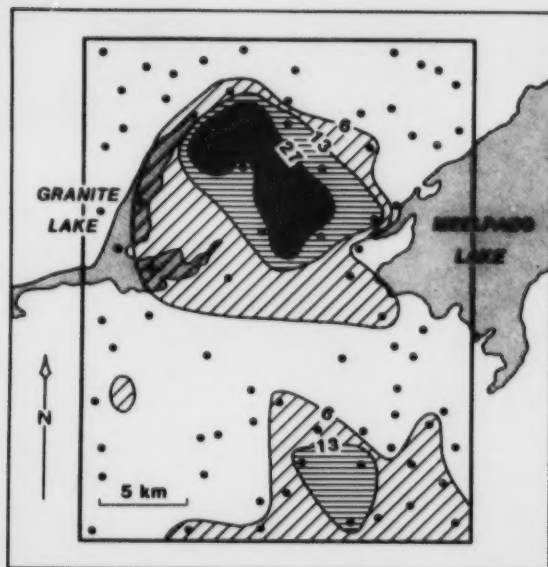


Figure 32.8. Distribution of W (ppm) in lake sediments at Granite - Meelpeag Lakes, south-central Newfoundland (after Davenport and Butler 1982).

(Figure 32.8) (Davenport and Butler 1982). The 25 km² area of mainly wolframite and molybdenite mineralization between Granite and Meelpeag Lakes is within and external to a massive pink biotite-muscovite granite and is also related to north-northwest- and northeast-trending fractures (Tuach and Delaney 1987).

As shown in Figure 32.8, at a regional sampling density of about one sample per 4 km², the central target and general areas of W mineralization are clearly defined by the 27 ppm W contour and a background cut-off contour of 6 ppm W. According to Davenport and Butler (1982), W does appear to be mobile in surface waters, dispersing in the drainage system and then concentrating in the lake sediments of the area. The source of the anomalous W is likely to be the tungsten mineralization, but some portion of the W may also be derived from the tungsten-rich (5 to 50 ppm) micas in the granitoid rocks (Davenport and Butler 1982). Therefore, W in lake sediments have effectively located an area of known tungsten mineralization. As a result, W analysis was added to some NGR lake sediment surveys beginning in 1984.

RARE EARTH ELEMENTS

Data for La and REEs were compiled from 136 analytical pairs of lake sediment samples and lake sediment reference standards to determine ranges, means, and to establish detection limits (P.H. Davenport, Senior Geochemist, Newfoundland Department of Mines and Energy, St. John's, Newfound-

land, Canada, personal communication, 1987). These data, which are summarized in Table 32.1, were produced by multi-element neutron activation analysis. The data indicate sufficient range for geochemical contrast in lake sediments was found and, except for Eu, the ranges are readily detectable. There is some difference in the detection limits quoted and those actually acceptable.

An example of the effective use of REEs in lake sediment geochemical exploration is described at the Strange Lake Zr-Y-Nb-Be-REE deposit (J.W. McConnell, Geochemist, Newfoundland Department of Mines and Energy, St. John's, Newfoundland, Canada, personal communication, 1987). The deposit is in a peralkaline granite complex on the provincial border with Québec, 145 km west of Nain, Labrador.

The deposit was discovered in 1979 by the Iron Ore Company of Canada during an exploration program following up U and F anomalies in lake sediments and waters shown on geochemical maps released under the Canada-Newfoundland Uranium Reconnaissance Program (Geological Survey of Canada 1979).

Samples of till, stream and lake sediment, and water were collected over 800 km² of the granite hosting the deposit (McConnell and Batterson 1987). Glacial erosion forms an eastward dispersal pattern up to 40 km in length in the various sample media. Dispersal patterns in till are strong, linear, and narrow, relative to the somewhat wider pattern found in the streams for a number of indicator elements including Be, Pb, Nb, La, and Y. Lakes, which provide the widest dispersal pattern, were initially proven useful for Be and Pb in the sediment and F in the water. Additional data for La and REEs in lake sediment (J.W. McConnell, Geochemist, Newfoundland Department of Mines and Energy, St. John's, Newfoundland, Canada, personal communication, 1987) have produced very long broad down-ice direction anomalies as illustrated by Yb (Figure 32.9). The heavier REEs provide a stronger dispersal pattern. The spatial distribution and contrast of the La and REE anomalies in lake sediment are as effective as related elements in other sample media for delineating a strong regional geochemical target. Lake bottom sediment surveys including La and REE data have a high potential for successful application in other areas of Canada.

PLATINUM GROUP ELEMENTS

There is very little published data on the content and distribution of PGEs in lake sediments of the Canadian Shield. The author has acquired a limited data set for 165 lake sediment samples from five mafic/ultramafic areas of PGE mineralization in northwestern Ontario (P.W.B. Friske, Head, Regional Studies Section, Geological Survey of Canada, Ottawa, personal communication, 1987). Archived samples from regional geochemical surveys in this area were

TABLE 32.1. DATA FOR La AND REE'S PRODUCED BY MULTI-ELEMENT NEUTRON ACTIVATION ANALYSIS.

ELEMENT	DETECTION LIMIT PPM		ABUNDANCE IN LAKE SEDIMENT PPM	
	QUOTED	ACTUAL	RANGE	GEOMETRIC MEAN
Ce	3	3	4.8 - 608	102
Eu	0.2	≈0.5	<0.2 - 5.3	1.2
La	1	1	5.7 - 304	44
Lu	0.05	≈0.05	<0.05 - 3.5	0.4
Sm	0.1	≈0.1	0.34 - 53	7.3
Tb	0.5	0.5	<0.5 - 9.3	1.1
Yb	0.1	≈0.5	<0.1 - 27.3	2.1

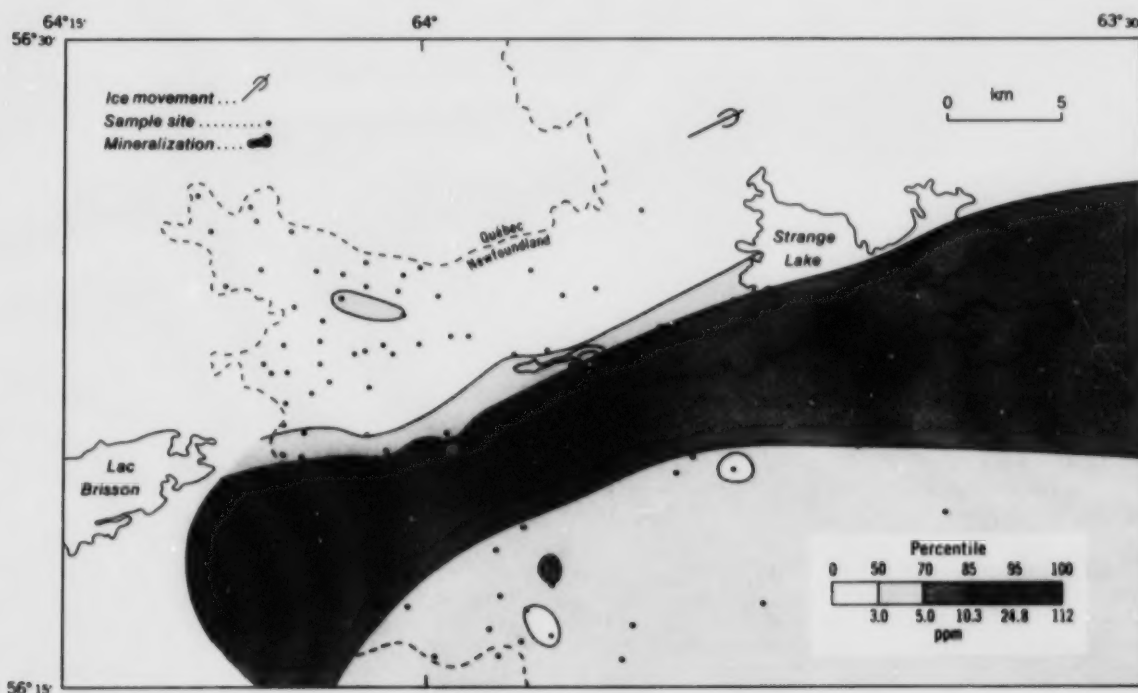


Figure 32.9. Distribution of Yb in lake sediments; Strange Lake REE deposit, Labrador (J.W. McConnell, Geochemist, Newfoundland Department of Mines and Energy, St. John's, Newfoundland, Canada, personal communication, 1987).

retrieved and analyzed for Pt, Pd, and Au by a Pb fire assay—inductively coupled plasma—mass spectrometer method. Results from the Lac des Iles area are shown in Figure 32.10 The Roby Zone, the largest showing of several PGE occurrences in the area, is located about 1 km south of Lac des Iles at the "X" within the Lac des Iles gabbro.

Anomalous levels of Au, Pt, and Pd occur in the vicinity of the mineralization (see Figure 32.10) and show evidence of down-ice displacement of the anomaly. The highest Pt value of 15 ppb was found in the sample from Camp Lake which is the focal point for the drainage system around the Roby zone.

The median Pd value for samples from the area is 6 ppb compared to 2 ppb for the total data set. This is evidence of some enrichment of Pd levels in the lakes reflecting the mineralization and/or the ultramafic complex.

Although detection limits of 1 or 2 ppb have since become available, work is still in progress (G. Hall, Head, Analytical Method Development, Geological Survey of Canada, Ottawa, personal communication, 1987) to further lower these to 0.1 ppb for Pt and Pd to better define background levels of Pt and Pd distribution. Additional data for Cu, Ni, Co, Cr, and Mg, as well as other routine regional

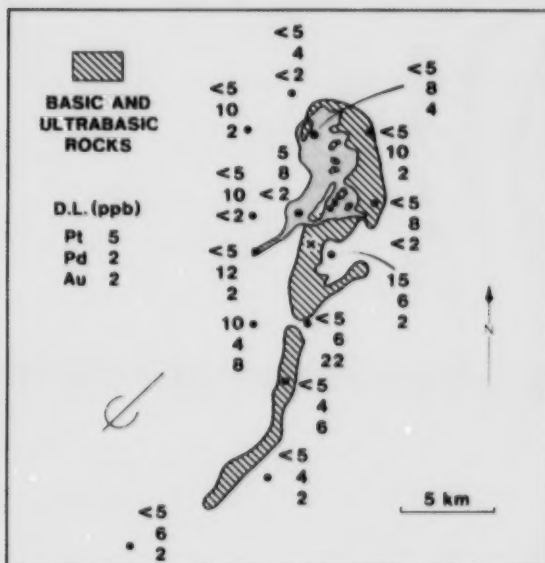


Figure 32.10. Distribution of Pt, Pd, and Au in lake sediments, Lac des Iles Area, northern Ontario (Roby zone X) (P.W.B. Friske, Head, Regional Studies Section, Geological Survey of Canada, Ottawa, personal communication, 1987).

survey elements, clearly outline the intrusive gabbro and would also have directed exploration into the area.

A combination of Pt, Pd, and Au and other elements have regionally identified the Lac des Iles gabbro and targeted areas of mineralization. At lower detection limits, the effectiveness will be improved. It appears, from the limited data available, that exploration for PGEs can be successfully carried out using lake sediments as a sample media.

GOLD

Currently, much exploration is focused on the search for gold in Canada and worldwide. Centre-lake bottom sediments have been employed as a geochemical sample media in exploring for gold. The interpretation of lake sediment gold data can be difficult, as illustrated below, because of its nature and distribution—a feature commonly referred to as the nugget effect or particle sparsity effect (Harris 1982). As described by Harris, gold only needs to be present as microscopic dust to randomly cause the problem of unacceptable precision in repeat analysis. The work of Coker *et al.* (1982) and Gregoire (1985) have demonstrated that particulate gold as well as organically or chemically bound forms commonly occur together in lake sediments. Fortunately, many of the commonly associated pathfinder elements for gold such as As, Mo, Sb, Hg, W, and, U do not have this problem.

The table of gold values (Table 32.2) illustrates the best and the worst situations that may occur with gold data from lake sediments. These data were selected from thousands of pairs of gold determinations from 1987 Ontario and Manitoba data sets. In most cases, the repeats were close or similar in the sense that the site was still considered anomalous. For example, 8 to 9 ppb or 3 to 2 ppb are similar and 32 to 17 ppm is still anomalous. However, 394 to <2 ppb and 172 to <2 are a problem and likely reflect the nugget effect. In some ways <1 to 17 ppb is even a worse situation, because in most cases, values such as 394 or 172 would be routinely reanalyzed, whereas samples with below detection limit values would not be. This situation may result in non-detection of anomalous sites. In rare cases, insufficient sample material was available for a repeat (i.e. 125 ppb value on 2.8 gm). The detection limit for gold changes with sample weight, as shown in Table 32.2, confirming the necessity to collect sufficient material to allow at least two determinations at full sample weight.

TABLE 32.2. GOLD VALUES FROM LAKE SEDIMENTS.

Au-1 (ppb)	Au-2 (ppb)	Wt-1 (gms)	DL-1 (ppb)	Wt-2 (gms)	DL-1 (ppb)
8	9	10.0	1	10.0	1
2	5	10.0	1	10.0	1
6	<1	10.0	1	10.0	1
394	<2	10.0	1	5.0	2
172	<2	10.0	1	5.0	2
<1	17	10.0	1	10.0	1
32	17	10.0	1	10.0	1
11	3	10.0	1	2.5	4
125	-	2.8	4	-	-
4	14	10.0	1	1.0	10
3	2	10.0	1	10.0	1
4	2	10.0	1	7.5	1

It appears that the gold reproducibility problem is less evident in lake sediments as the organic content increases. This is illustrated by a modified plot of 50 duplicate gold analyses on lake sediments from northwestern Ontario (Figure 32.11). Gold repeat values are more variable in samples with lower loss on ignition (LOI) values. Of the 22 samples with less than 11 percent LOI, five had repeat gold values where the gold changed from background to anomalous or the reverse. In the range of 11 to 19 percent LOI, two pairs changed and where LOI values exceeded 20 percent, no pairs changed. This is not a guarantee that samples with high LOI values over 20 percent will never have a nugget effect problem, but is an indication that they have a significantly better chance of acceptable repeatability. The geometric mean for Canadian Shield, Boreal Forest lake bottom sediments exceeds 20 percent LOI (Coker *et al.* 1979). The increased variability in the low LOI range probably reflects the largely clastic character of the sediment and the greater possibility of containing detrital gold.

Unlike many other elements, one of the benefits of using gold is that it is not influenced by organics, Mn, or Fe in lake sediments. This is demonstrated in Figure 32.12 where the X-Y plots of Au versus Fe, Mn, and LOI, using data from northern Ontario, show no demonstration of a sympathetic relationship (P.W.B. Friske, Head, Regional Studies Section, Geological Survey of Canada, personal communication, 1987). Gold values will, therefore, most often be reflecting enhanced bedrock concentrations and/or gold-bearing mineralization rather than false anomalies generated by the scavenging ac-

tion of Fe and Mn oxides and hydroxides or organics.

Evidence of successful regional gold exploration using lake sediments is provided in the East Kemptville, Nova Scotia area previously described. The Kempt Back Lake gold mineralization (Figure 32.13) was detected (Rogers 1986) and a new

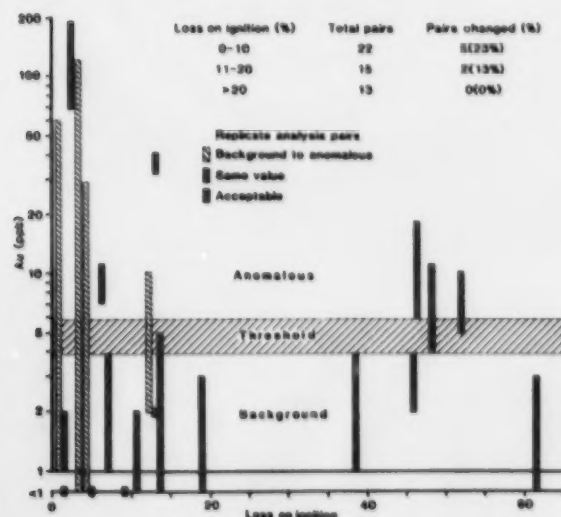


Figure 32.11. Replicate pair Au analyses in relation to the organic content of the lake sediment samples. The ends of the vertical bars represent the two gold values.

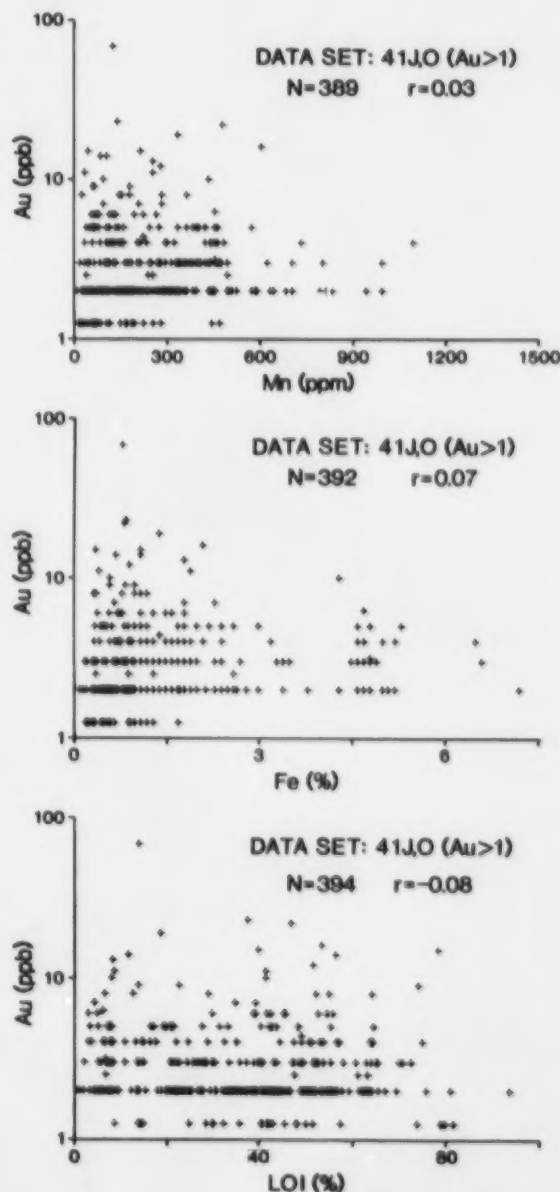


Figure 32.12. The relationship of gold to the organic content (LOI) of and Fe and Mn in lake bottom sediments (P.W.B. Friske, Head, Regional Studies Section, Geological Survey of Canada, Ottawa, personal communication, 1987).

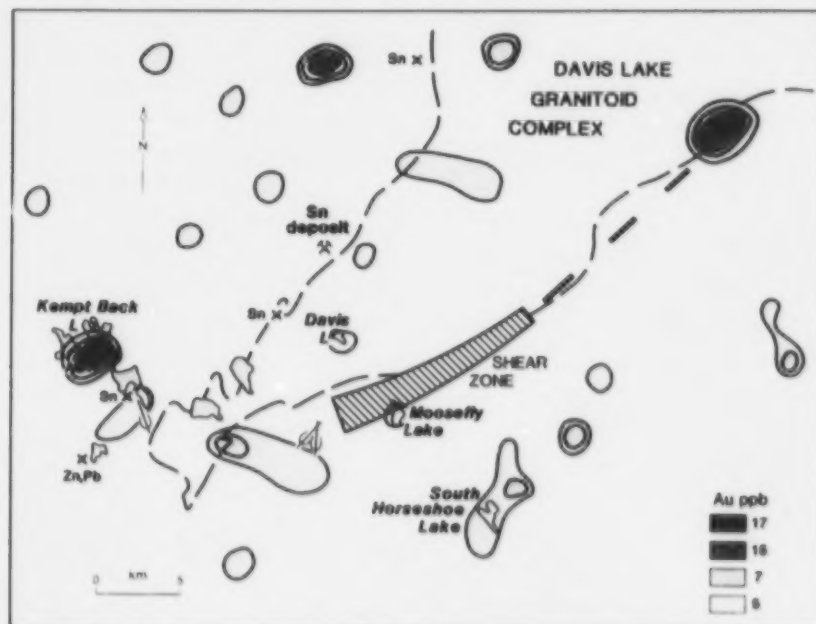


Figure 32.13. Distribution of gold in lake sediments; East Kemptville tin deposit area, Nova Scotia (modified after Rogers 1986).

anomalous area was discovered and later staked along the granitoid-metasediment contact on the northeastern extension of a shear zone (P.J. Rogers, Geochemist, Nova Scotia Department of Mines and Energy, Halifax, Nova Scotia, Canada, personal communication, 1987).

Another example is from the Hemlo gold camp of northwestern Ontario before the landscape was geochemically contaminated. Figure 32.14 shows the Au, Mo, and As values for some of the 150 samples collected in the area. Lake sediments from Moose Lake, the focal point for drainage in the vicinity of the Hemlo deposits are definitely anomalous for all three elements. The Au concentration in Moose Lake of 6 ppb and that of nearby lakes contrasts well with the less than 1 ppb local background. Not shown is an Sb value of 8 ppm in Moose Lake that also is in high contrast to a background value of less than 0.2 ppm.

The work of Coker *et al.* (1982), Thomas (1986), and Schmitt and Friske (1987) in Saskatchewan and McConnell (1987) in Newfoundland have also demonstrated the effectiveness and problems of gold data in lake sediment exploration. The use of centre-lake bottom sediments for gold and related pathfinder element exploration has become an established method with appropriate consideration for the problems of repeating gold analyses.

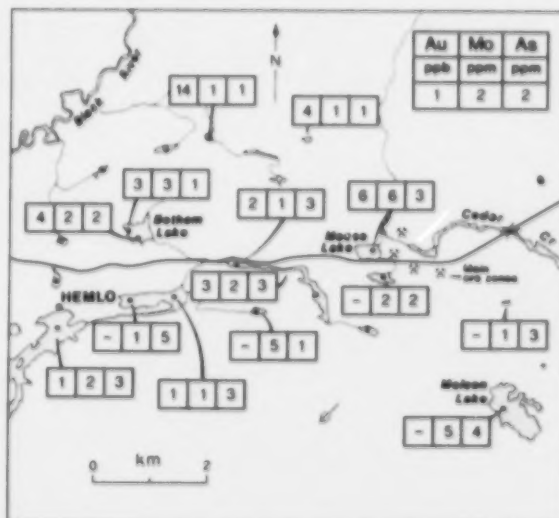


Figure 32.14. Distribution of Au, Mo, and As in lake bottom sediments, Hemlo gold camp area, Ontario, (~ Au value below the <1 ppb detection limit).

CONCLUSIONS

Subbottom acoustic profiling can be used to map glacial and lacustrine sediment facies in lakes of the Canadian Shield and significantly aid in the geochemical interpretation of lake sediment survey data. Regional geochemical lake sediment survey coverage of Canada amounts to 1.1 million km². Together with other geoscientific data, it provides a valuable data base for governments, the mineral industry, and environmental and public health concerns. The 1980s have seen new and potential applications for lake sediment geochemistry for Au-, Sn-, W-, PGE-, and REE-bearing mineralization.

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33. Developments in Biogeochemical Exploration

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ABSTRACT

The use of biogeochemical methods in exploration has been more extensively examined over the past decade than ever before, thanks largely to great improvements in analytical technology. International symposia, workshops, scientific publications, and several new books on the subject have helped to demonstrate the value, and the limitations, of biogeochemical methods to the exploration community.

Emphasis has been on the chemical analysis of living plant tissues for uranium, precious, and base metals. However, a number of studies have evaluated other elements and other biological materials, such as peat, forest litter, and plant sap, and have exploited the information to be gleaned from the Animal Kingdom (notably bees). A major new thrust has been in the application of microbiological methods, by examination of the relationship between bacterial populations in the soil and underlying zones of mineralization.

Base line data are now available for a wide spectrum of elements in many common plant species, providing the basic information required by exploration geologists for evaluating new biogeochemical data sets. Biogeochemistry is "coming of age".

INTRODUCTION

NEW BOOKS

During the past decade, four major new English-language textbooks on biogeochemical exploration for minerals have been published: Kovalevskii 1979; Brooks 1983a; Brooks and Malaisse 1985; and Carlisle *et al.* 1986. Kovalevskii's book is a translation of his 1974 text which contains significantly more quantitative information than the English translation of an earlier milestone book in Russian by Malyuga (1964). Kovalevskii provides a most informative insight of the Russian approach toward biogeochemical exploration, and provides a wealth of tabular and graphical chemical data from a wide range of plant species.

In 1983 Brooks published a second edition of his classic text (Brooks 1972) on geobotanical and biogeochemical methods of mineral prospecting. This new text includes an abundance of new material and references, and provides the first compilation of geozoological techniques (i.e. the use of ani-

mals and insects in assisting the prospector). The following year he coauthored a book that dealt in detail with the heavy-metal-tolerant flora of south-central Africa (Brooks and Malaisse 1985).

In 1983 a symposium entitled "Organic Matter, Biological Systems and Mineral Exploration" was held in Los Angeles. The proceedings were published in a significant volume which combines, for the first time, a series of biogeochemical review papers and case histories, with sections on the microbiological approach to prospecting, and the use of humic substances (Carlisle *et al.* 1986).

A fifth text of value to anyone involved in the use of soils or plants in exploration was published by Kabata-Pendias and Pendias (1984). This is a useful compilation of data on trace-element movements and concentrations in soils and the biosphere (i.e. "the natural environment of living things...the biological epidermis of the earth whose dimensions are not precisely defined" *op. cit.*, p.1).

There has emerged from the press, just in time for this review, another book by the prolific R.R. Brooks, entitled "Serpentine and its Vegetation: a Multidisciplinary Approach" (Brooks 1987). For "Serpentine" the geologist should read "Ultramafic Rocks", since the author has bowed to the general usage of the botanist rather than the stricter definition of the geologist. In that ultramafic rocks are currently being eyed with keen interest by many exploration groups interested in the platinum group metals, this new text is a timely and welcome encyclopedic compilation of about one thousand papers on the flora characteristic of this important group of rocks. A rather small percentage of the book is devoted directly to biogeochemical exploration, reflecting the need for more research in this area.

Two more texts will be of interest to those attempting to use plants to help in the discovery of mineralized zones. The first is in press (scheduled to be published in November 1987), and is entitled "The Practical Applications of Trace Elements and Isotopes to Environmental Biogeochemistry and Mineral Resources Evaluation" (Hurst *et al.*, in press). The second book has been published already, but only in Russian (Kovalevskii 1984b) although a translation into English is in preparation (Kovalevskii, personal communication, 1987). This is a second and thoroughly revised edition of his earlier work mentioned above, which contains a great deal of fundamental new information and data (particularly on mercury, silver, cadmium, tin, niobium, vanadium, chromium, and thallium).

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THE JOURNALS

Scientific journals contain a steadily increasing number of papers that deal with biogeochemical exploration. A journal entitled "Biogeochemistry", that first appeared in 1983, covers the broad spectrum of the subject, with most papers directed to environmental studies (mainly major elements) with some of more direct application to mineral exploration (trace elements).

The majority of research papers published in English, that are related to mineral exploration, can be found in the Journals of Geochemical Exploration, Applied Geochemistry, Geochemistry, and Geochemistry International. It is difficult to determine exactly how many papers on biogeochemical exploration have been written over the period, since biogeochemistry covers such a broad spectrum of disciplines. In order to extract facts which may be of pertinence to exploration, it is necessary to conduct literature searches which include geology, chemistry, botany, zoology, microbiology, environmental studies, remote sensing, and even health studies (epidemiology). From the resultant morass of information, it appears that over the past ten years a minimum of two hundred and fifty papers have been published (in a variety of languages, but mainly in English and Russian) which are of direct relevance to the use of organic media for mineral exploration. Of these papers, the majority deal with gold (25 percent), uranium (15 percent), and base metals (15 percent). A further 10 percent are review papers (Table 33.1).

WORKSHOPS

The Association of Exploration Geochemists has recognized the potential value of biogeochemical methods applied to exploration and, in response to

the curiosity and demands of the exploration community at large, has organized workshops on this topic at its international meetings in Helsinki, 1983 and Toronto, 1985. When compared to other geological subdisciplines, there are few active "exploration biogeochemists"; hence, these workshops (and the 1983 Los Angeles symposium previously mentioned) have been of immense value in bringing together western and eastern bloc scientists for the exchange of information and ideas. Summaries of these workshops were published by Erdman and Kukkola (1984), and Dunn (1987a).

Late in 1984 a symposium on geobotany and biogeochemistry was held in Tirupati, India. Part of this meeting had a different slant from the pure exploration for minerals, since the role of plants in helping to locate groundwaters was examined. Most studies were from India and the proceedings volume, scheduled to be published soon, will provide much-needed information on biogeochemical exploration in the semi-arid tropical environment.

THE INCREASING ROLE OF BIOGEOCHEMISTRY IN EXPLORATION PROGRAMS

Interest in the use of plants to assist in the discovery of mineralization has gained considerable momentum over the past decade, particularly in the boreal forests and semiarid areas of the world. In the Soviet Union, biogeochemistry is accepted as a common-place exploration method, and has led to the discovery of four major mineral deposits between 1978 and 1982 (Kovalevskii 1984a). Indications are that the science of biogeochemistry is more advanced in the Soviet Union than in North America, since the Soviet baseline information comprises studies on over one million samples against which survey data can be evaluated (Kovalevskii 1984a).

The more innovative exploration companies in North America, when planning an exploration program, now give close attention to the possible use of plant chemistry as a guide to mineralization concealed beneath the veneer of overburden that extends across vast expanses of the continent. There is evidence to clearly demonstrate that the immense physical and chemical power of plant roots is sufficient to extract every element of the periodic table from soils, bedrock, and groundwaters. Once in the plant's juices, elements are translocated to different plant organs, depending on plant species, and concentrated to varying degrees. The past decade of research has expanded considerably both the data base and our understanding of the complex processes controlling the uptake, translocation, and fixation of elements in the biosphere.

A measure of the level of activity in biogeochemistry is the dramatic increase, reported by analytical companies, in numbers of "biological" samples submitted for analysis in recent years. In-

TABLE 33.1. APPROXIMATE DISTRIBUTION (BY TOPIC) OF PAPERS ON BIOGEOCHEMICAL EXPLORATION, PUBLISHED BETWEEN 1977 AND 1987.

TOPIC	PERCENTAGE OF PAPERS
Gold	25
Base Metals	15
Uranium	15
Reviews	10
Copper	5
Nickel	4
Molybdenum	3
Peat and Humus	3
Microbiology	3
Bryophytes	3
Geozoology	3
Geobotany	3
Other	8
Total	100%

deed, it is largely due to the remarkable improvements in analytical technology that biogeochemistry has become a viable method of exploration. A major contributing factor to this renewed interest has been the refinement of instrumental neutron activation analysis (INAA); for example, Minski *et al.* (1977), Vaganov *et al.* (1977), Valente *et al.* (1982), Hofman and Brooker (1986). The INAA of dried or ashed vegetation for over thirty elements, now costs no more than a standard soils 'base-metal' atomic absorption package for seven to eight elements, of ten to fifteen years ago. Similarly, the ICP (inductively coupled plasma emission spectrometer) provides multi-element analysis at low cost, and the new development of coupling the ICP to a mass spectrometer further improves sensitivity. This great improvement in sensitivity (with concomitant precision) has provided a new breath of life to biogeochemistry. Accurate and precise sub-ppm analysis for many elements (and sub-ppb levels for gold) is commonplace, and cheaper now than it has ever been. Such high quality analysis is essential for routine determination of the small traces of many elements that occur in plants, in order that subtle variations attributable to mineralization may be discerned.

PRECAUTIONS AND PROBLEMS

There has developed a greater awareness of some of the precautions that need to be taken when conducting biogeochemical surveys. Many studies have continued to document the great differences of element uptake that there are among species, and the considerable variations that occur in the different tissue types of an individual plant (e.g. Chukhrov *et al.* 1979; Kovalevskii 1979; Dunn 1981, 1986b, 1986c; Brooks 1982, 1983a; Warren *et al.* 1983; Cohen *et al.* 1987). This has led to a more rigorous control of sampling methods, especially that basic ingredient of any scientific study: "consistency". For example, the awareness that plant chemistry varies from one year's growth to the next (e.g. Dunn 1983a) has generated sampling programs designed to collect a specific number of years of growth from a particular species at each sample site, and (preferably) from plants of similar age, growth patterns, and appearance. Furthermore, the greater recognition of seasonal and annual variations in plant chemistry permits better interpretation of biogeochemical data (e.g. Dunn 1983a, 1986b, 1986c; Cohen *et al.* 1987; Stednick *et al.* 1987; Stednick and Riese 1987).

In recent years it has become increasingly evident that plant chemistry does not always faithfully reflect the chemistry of the soil in which the plant is rooted. This lack of correlation is particularly apparent in glaciated terrains, where elements dissolved in migrating groundwaters appear to have a closer con-

trol than soil composition on the plant chemistry (Kitaev and Zhukova 1980; Dunn 1983a; Kapustina and Ushakov 1984). The last of these three studies shows that the plant chemistry was more effective than the soil chemistry in delineating the extent of a quartz-scheelite stockwork. Similarly, Cohen *et al.* (1987) found that plants growing over gold mineralization in Ontario outlined a broader halo of mineralization than did the soils; therefore, fewer vegetation than soil samples need be collected to define the exploration target.

The debate continues as to whether or not plant material should be ashed prior to analysis. It has been established that some elements volatilize from some species during ashing (Girling and Peterson 1978). Ashing significantly concentrates elements and, if wet chemical methods are to be employed, analysts have a strong preference for dealing with ash. However, INAA does provide excellent data on pellets of dried material, so ashing is no longer a prerequisite for obtaining reliable data at low cost provided, of course, that one has ready access to INAA.

One advantage of ashing is that a relatively large sample can be analyzed: 50 to 100 g of most types of dried tissue will reduce to about 1 g of ash. In order to digest with acids this much dry material, a long and relatively expensive digestion is required. However, because of the chemical inhomogeneities in plant material, it is desirable that the sample to be analyzed be as large as is practically possible; ashing achieves this goal. Dunn and Hoffman (1986) noted that although the organic complexing of trace metals in plants has a profound effect on the retention of these metals during ashing, it is significant to biogeochemical prospecting that the chemical species retained in the ash may be related to the presence of mineralization; even some species of mercury are retained after ashing (Kovalevskii 1986a).

A study of elements in the ash of plants growing over different rock types in Germany and Norway has provided a good broad indication of the lithological control of element concentrations, and the background levels that might be expected (Pape 1981).

Chukrov *et al.* (1979) observed that the percentage of ash is related to the intensity of weathering of the parent rock. This is of fundamental importance in understanding biogeochemical data, and demonstrates the requirement that "loss on ignition" (LOI) must be taken into account when interpreting biogeochemical data. If there is little variation in LOI, then data may be expressed on either an ash or dry-weight basis. If LOI varies substantially, then a normalization procedure should be performed. It is noteworthy, too, that a map plot of ash content of plants may provide valuable information on the distribution of bedrock-weathering intensity.

EXPLORATION FOR SELECTED COMMODITIES USING HIGH ORDER PLANTS

URANIUM

The oil crisis of the early 1970s sparked intense activity toward the development of alternative fuel sources—notably uranium. Exploration companies tried every conceivable method that might give them the competitive edge in the discovery of mineralization. Biogeochemistry was among the more abstruse methods investigated, notably by a study group established under the umbrella of the Nuclear Energy Agency and the International Atomic Energy Agency (NEA and IAEA). A product of this group was a publication summarizing the world literature on uranium biogeochemistry that contained also a significant contribution by Alexander Kovalevskii (Dunn *et al.* 1985). It transpires that over two hundred papers have been written that contain information of relevance to uranium biogeochemistry in a wide range of languages, but over half are in Russian. This attests to the extent and the seriousness with which the Russians have applied to biogeochemistry.

During this flurry of uranium exploration activity, an interesting biogeochemical study in northern Saskatchewan conducted by Walker (1979) was followed by extensive surveys over the poorly exposed Athabasca Group, which revealed a biogeochemical anomaly of extraordinary proportions. Contained within this anomaly, there are known to occur about a dozen major uranium deposits. Ashed twigs of black spruce (*Picea mariana*) were found to contain up to 2270 ppm U (normal background is about 3 ppm U), and all spruce trees sampled (about 2000) in an area of 10 000 km² had greater than three times background levels of uranium; within this area all spruce trees in the central core of 1000 km² contained uranium concentrations of over thirty times background in their twig ash (Dunn 1982, 1983a, 1983b). This showed the potential value of using biogeochemistry as a regional exploration tool; moreover, in this unusual case a sample density of only 1 per 1000 km² would have been sufficient to outline this major 'Wollaston Uranium Biogeochemical Anomaly'.

On a detailed scale, local enrichment of uranium in vegetation was evident over zones of mineralization buried deep beneath the Athabasca sandstones (Dunn 1981, 1983b). Similarly, Brooks (1982) reported a positive response to mineralization in red spruce (*Picea rubens*) from a uraniferous area of Nova Scotia. In contrast to the observation made in the boreal forest that the twigs concentrate uranium to higher levels than leaves, studies over the Ranger One Deposits in Australia showed the highest concentrations to occur in leaves of members of the Myrtaceae Family (e.g. eucalypts, Cruickshank and Pyke 1986).

In the semi-arid western United States, Erdman and Harrach (1981) found that big sagebrush (*Artemisia tridentata*) was an appropriate sample medium; more recently, hydroponic experiments provided evidence to suggest that uranium tends to behave as an essential element in this plant species (Diebold and McGrath 1985). Even in deserts, the palm tree (*Phoenix dactylifera*) can be used in uranium prospecting. In this case, though, absolute concentrations of uranium are not as important as the uranium isotopic disequilibria of their associated water sources, which they reflect (Kronfeld and Zafirir 1982). This disequilibrium can be of use in defining prospect target areas.

PRECIOUS METALS

Gold

As the price of uranium steadily declined, the attention of the mining industry was turned toward gold. This required a whole new exploration strategy and evaluation of exploration methods, and again consideration was given to the use of plant chemistry. Studies were directed to new areas and problems by building upon the earlier work by, amongst others, Talipov and Kovalevskii in the Soviet Union, Warren in Canada, and Shacklette and Jones in the United States (e.g. Talipov *et al.* 1968, 1974, 1975; Kovalevskii and Prokopchuk 1978; Warren and Delavault 1950; Warren *et al.* 1964; Shacklette *et al.* 1970; Jones 1970). Table 33.2 gives reference to those papers in the last decade which have information of relevance to biogeochemical exploration. The summary by Erdman and Olson (1985) is a particularly valuable compilation which has assisted in the present review.

The claim that horsetails (*Equisetum* sp.) can accumulate extraordinary amounts of gold was disproven by Cannon *et al.* (1968), reclaimed by Brunsell (1978), and finally laid to rest by Brooks *et al.* (1981). However, horsetails can accumulate arsenic, and because of the common geochemical association of gold and arsenic, horsetails may be of use as indirect indicators of gold mineralization.

In a review of biological methods of exploration for gold, Brooks (1982) noted that no plant is known to be a geobotanical indicator of gold; i.e. no plant has been found that is restricted in its occurrence to zones of known gold mineralization.

A significant study by British and Canadian researchers showed that on ashing, some vegetation species lose their gold content in the form of a cyanide (Girling and Peterson 1978; Girling *et al.* 1979). Certain species contain cyanogenic glycosides which combine with the contained gold to volatilize as a gold cyanide, well below the normal ashing temperature of about 500°C. Their 1978 study also examined the distribution of gold in some laboratory-grown plants, by using a radioactive isotope of gold in solution. They observed that most of the gold mi-

TABLE 33.2. SUMMARY BY TOPIC OF PAPERS PUBLISHED FROM 1977-1987 FOUND TO CONTAIN INFORMATION OF VALUE TO BIOGEOCHEMICAL EXPLORATION.

BIOGEOCHEMICAL ENVIRONMENT		Boreal Environ. (cont.)	Main Topic(s) (cont.)
Temperate Environment	Main Topic(s)		
Al Ajely <i>et al.</i> 1985	Base metals, Sr, Rb, Cl, I	Dunn 1985	Au
Arribas and Herrero-Payo 1979	U	Dunn 1986a	Au, W, U
Baker 1986a	Au	Dunn 1986b	Au, Pt, Pd
Banville 1987	Au	Dunn 1986c	Au
Bélanger, in press	Ni+	Ek 1982	U
Blondiaux <i>et al.</i> 1978	Serpentinities	Erdman and Motooka 1985	Base metals
Bouda 1986	U	Fedikow 1983	Base metals, Au, Ag
Brooks <i>et al.</i> 1982	U	Fedikow 1984	Base metals, Au, Ag
Castle 1980	Cu, Mo	Fedikow 1985	Base metals, Au, Ag
Clayton 1980	Cu	Fedikow 1986	Base metals, Au, Ag
Cook <i>et al.</i> 1982	U	Konstantinova and Rusyeyeva 1977	Au
Crisci <i>et al.</i> 1982	Sulphides	Sheppard and Thibault 1984	U
DiLabio <i>et al.</i> 1982	Zn, Cd	Walker, 1979	U, N
Fuzaylov and Koval'skiy 1981	Sb		
Girling <i>et al.</i> 1978	Au, As	Arid and Semi-Arid Environment	Main Topic(s)
Girling <i>et al.</i> 1979	Au	Bogoch and Brenner 1984	Cu
Goff <i>et al.</i> 1985	Au	Butt and Smith 1980	General
Johannes and Krause 1985	Base metals	Cruikshank and Pyke 1986	U
Kapustina and Ushakov 1984	W	Cruzat 1984	Au+
Kaspar 1983	Sn	Dean and Gulson 1987	Pb isotopes
Kelepertsis and Andriulakis 1983	Sulphides	Diebold and McGrath 1982	U
Kelepertsis <i>et al.</i> 1985	Base metals	Erdman and Harrach 1981	U
Kothny 1979	Pd	Gough and Severson 1981	Variability
Leavitt and Goodell 1979	Sulphides	Kronfeld and Zafrir 1982	U
Leonard and Erdman 1983	Au, Mo, W	Lezhneva 1978	Au, W
Leonard <i>et al.</i> 1985	Au, Mo, W	Lezhneva 1980	Sn
Minski <i>et al.</i> 1977	Au, As (INAA)	Lovering and Hedai 1983	Base metals
Nash and Ward 1977	U	Moriel 1983	Base metals
Reeves <i>et al.</i> 1986	Sulphides	Robinson 1986	Base metals
Riese and Arp 1986	Pt	Santra <i>et al.</i> 1982	Cu
Russell and van Moort 1981	Base metals, Ba, Cd	Talipov and Tverskaya 1984	W
Ryall and Nicholas 1979	Base metals	Talipov <i>et al.</i> 1978	Au
Smith and Fournier 1986	Sulphides	Talipov <i>et al.</i> 1985	As, Sb
Stednick and Riese 1987	Au, temporal studies	Talipov 1977	Pyritiferous ore
Stednick <i>et al.</i> 1987	Au, temporal studies	Taylor 1977	Base metals
Valente <i>et al.</i> 1986	Au	Arctic Environments	Main Topic(s)
Ward and Brooks 1978	Au	Bollingberg and Cooke 1985	Pb, Zn
Warren and Horsky 1986	Au, Ti	Geological Surveys of Finland, Norway, and Sweden 1986	Multi-element regional surveys
Warren <i>et al.</i> 1983	Hg	Reading <i>et al.</i> 1987	Au
Warren <i>et al.</i> 1984	Ag	Vaganov <i>et al.</i> 1977	Hg
Warren 1978	Pb		
Boreal Environment	Main Topic(s)	Tropical (Humid Environments)	Main Topic(s)
Brooks <i>et al.</i> 1979	Cu, Pb, Ni	Baker <i>et al.</i> 1985	Ni
Brooks <i>et al.</i> 1981	Au	Brooks and Wither 1977	Ni
Cohen 1986	Au+	Brooks and Yang 1984	Ni
Cohen <i>et al.</i> 1987	Au+	Brooks <i>et al.</i> 1978	Cu
Dunn and Hoffman 1986	REE	Brooks <i>et al.</i> 1985	Cu+
Dunn 1980	Au	Dakshini <i>et al.</i> 1982	Base metals
Dunn 1981	U	Das <i>et al.</i> 1977	Au
Dunn 1982	U	Dissanayake and Kritsotakis 1984	Au, Pt, algal mats
Dunn 1983a, b	U		

Continued

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TABLE 33.2. CONTINUED.

Hegde and Aswathanarayana 1977	Base metals	Unspec. (cont.)	Main Topic(s) (cont.)
Inasi and Gibbs 1982	Base metals, Na, Cr, Sn	Rusayeva and Gapon 1977	Au
Kiran and Bedi 1984	Base metals	Slacik <i>et al.</i> 1977	Sb
Mathur and Alexander 1983	Kimberlites	Talipov and Tverskaya 1979	Au
Prasad and Vijayasaradhi 1985	Cr, V	Tiffin 1977	Review of metals in plants
Prasad 1987	Review		Mo
Tiagi and Aery 1981	Zn	Yingjun and Chenqi 1985	W, Mo
Tiagi and Aery 1986	Cu		
Yang <i>et al.</i> 1985	Serpentinities	PEATS/HUMUS	MAIN TOPIC(S)
Unspecified or Worldwide	Main Topic(s)	Andrews and Fuge 1986	Cu
Berzina <i>et al.</i> 1982	B	Boyle 1977	Cu
Boyle 1980	U, Th	Brundin <i>et al.</i> 1987	Base metals, Cr, Mo, U
Brooks <i>et al.</i> 1977	Ni (Herbarium)		Fe
Brooks 1979	Review	Crerar <i>et al.</i> 1979	Humus, Review
Brooks 1982	Au review	Curtin and King 1986	Au+
Brooks 1983a	Textbook	Fortescue 1985, 1986	Au+
Brooks 1986	Review	Gleeson <i>et al.</i> 1986	U
Buehling <i>et al.</i> 1978	Be, review	Idiz <i>et al.</i> 1986	Humus, review
Carlisle <i>et al.</i> 1986	Textbook	Kokkola 1977	Humus, annual variations
Chukrov <i>et al.</i> 1978	Sulphides	Salminen and Kokkola 1984	Humic reactions
Chukrov <i>et al.</i> 1979	Cu, Zn		W
Connor and Shacklette 1984	Spanish Moss	Schnitzer 1986	MAIN TOPIC(S)
Davy and Ryall 1980	Review	Toverud 1979	Cu, Co
Dunn <i>et al.</i> 1985	U bibliography	MOSSES/BRYOPHITES	Au, Ag+
Dunn 1987a	Workshop review	Erdman and Modreski 1984	As, Bi
Erdman and Kokkola 1984	Workshop review	Jones 1985	Au, Ag
Erdman and Olsen 1985	Au review	King <i>et al.</i> 1983a	Mo, Sn, W
Gough <i>et al.</i> 1979	Toxicity, baseline data	King <i>et al.</i> 1983b	Cu Pb, Zn
	Plant surface particles	King <i>et al.</i> 1983c	Review
Horier <i>et al.</i> 1980	Sn	King <i>et al.</i> 1983d	U
Ivashov 1986	Au	Shacklette 1984	Base metals, Hg
Kitaev and Zhukova 1980	Au	Shacklette and Erdman 1982	MAIN TOPIC(S)
Kovalevskii and Prokopchuk 1978	Hg	Smith 1986	Oil
Kovalevskii 1977	Polymetallic ores	HYDROCARBONS	Oil
Kovalevskii 1978a	Be	Dalziel and Donovan 1980	
Kovalevskii 1978b	Biogeochem. halos	Roeming and Donovan 1985	
Kovalevskii 1978c	W		
Kovalevskii 1979	Book	GEOBOTANY	MAIN TOPIC(S)
Kovalevskii 1983	Review	Anderson 1983	Review
Kovalevskii 1984a	Book	Bell <i>et al.</i> 1985	Delay in leaf flush
Kovalevskii 1984b	Deep deposits	Brooks 1979a	Review
Kovalevskii 1985	Hg	Brooks 1979b	Review
Kovalevskii 1986a	Review	Canney <i>et al.</i> 1979	Autumn colours+
Kovalevskii 1986b	Sap, Au, Zn	Cole and Le Roex 1978	Africa
Krendelev and Pogrebnyak 1977	Sap, various elements	Cole 1980	Review
Krendelev and Pogrebnyak 1979	Sap, chemistry	Crossley 1984	Termites
	Mo	Czehura 1978	Cu, Ag
Krendelev <i>et al.</i> 1978	Multi-element	Pustovoyt and Turchinskiy 1984	Rare metal indicator
Orlov 1983	Biogeochem. haloes	Reeves and Brooks 1983a, b	Pb, Zn
Pape 1981		Wither and Brooks 1977	Ni
Rusayeva <i>et al.</i> 1979			

Continued

TABLE 33.2. CONTINUED.

GEOZOOLOGY	MAIN TOPIC(S)	Microbio. (cont.)	Main Topic(s) (cont.)
Bromenshenk <i>et al.</i> 1985	Bees	Watterson 1985	Bacillus cereus, procedure
Brooks 1983b	Review		
Prasad <i>et al.</i> 1987	Termites	METHODS	MAIN TOPIC(S)
Warren and Horsky 1982	Bee pollen	Brooks and Naidu 1985	Au-analytical
Warren 1980	Bee pollen	Campbell 1986	Coring device
		Fryer and Kerrich 1978	Au-Analytical
		Harms <i>et al.</i> 1981	U-Analytical
		Hoffman and Brooker 1986	Au-INAA
		Kothny 1987	Pt, Pt-analytical
		Singh <i>et al.</i> 1986	U-fission track method
			PGM + Au by NAA
MICROBIOLOGY	MAIN TOPIC(S)	Valente <i>et al.</i> 1982	
Colwell <i>et al.</i> 1986	Antibiotic resistance	PROCESSES	MAIN TOPIC(S)
Ehrlich 1986	Heavy metals	Baker 1986b	Humic substances
Michaels and Riese 1986a, b	Luminometry	Berry 1986	Plant factors
Michaels <i>et al.</i> 1985	Luminometry	Diebold and McGrath 1985	U, Lab. tests
Olson and Barkay 1986	Antibiotic resistance	Girling and Peterson 1978	Au uptake tests
Parduhn 1987	Bacillus cereus, Ph.D. Thesis	King <i>et al.</i> 1984	Metal uptake by conifers
	Bacillus cereus, Cu		Au from natural waters
Parduhn and Watterson 1984	Bacillus cereus, Au	Konstantinova 1981	Pt uptake by crops
Parduhn <i>et al.</i> 1985	Bacteria/heavy metals	Pallas and Jones 1978	Au
Tripp <i>et al.</i> 1986	Review	Talipov and Samigdzhanova 1979	Element uptake
	Au	Thornton 1986	
	Cu		
	Bacillus cereus, procedure		

grated toward the leaf tips. Empirical studies by Dunn (1986b) and Cohen *et al.* (1987) show that this 'acropetal' tendency occurs in some, but not all common boreal plants. For example, gold is more enriched in the twigs and bark of black spruce than it is in the needles. The importance of these observations is that, before deciding to ash a set of samples prior to gold analysis, it is critical to be aware that some gold may volatilize from some species. Fortunately, most plants in the boreal forests (except, perhaps, some members of the rose family) have gold combined in their cells firmly enough that volatilization does not readily occur during ashing.

Instrumental neutron activation analysis of dried pellets (8 g) of macerated vegetation can detect as little as 0.1 ppb Au, with no pre-concentration procedure. The same method can readily detect 5 ppb Au in ashed material (0.5 g). A wet chemical method involving the digestion of dry powdered plant material, was developed by Brooks and Naidu (1985) and claims a detection level of about 1 ppb Au. Warren and Horsky (1986) developed a method for determining down to a few parts-per-billion gold and thallium in dried plant material, and noted a remarkably close association of the two elements in several species from above a zone of gold mineralization in British Columbia.

Studies show that, in general, background levels of gold in plant ash are about 5 to 10 ppb; however, some phenomenal concentrations have been recorded. Baker (1986a) found 180 000 ppb Au in

ash (1900 ppb Au dry weight) in second year growth of pine twigs from Tasmania. In Saskatchewan, a sample of combined leaf and twig of alder has yielded 231 000 ppb Au (5000 ppb Au dry weight) in association with high levels of silver, arsenic, bromine, and cobalt (Dunn 1987b). The sources of these anomalies are currently being investigated.

In the semi-arid regions of the western United States, sagebrush and creosote bush are among the species which have been used to help delineate gold mineralization (Busche, in press). In more temperate zones, Erdman and others (e.g. Erdman *et al.* 1985; Erdman 1986) have studied the uptake of several metals in plants growing over the gold-molybdenum-tungsten stockwork at Red Mountain, Idaho. This study provides a good example of the value of using more than one plant species to assist in locating the zone of mineralization. The trunkwood of Douglas fir (*Pseudotsuga menziesii*) and the leaves of beargrass (*Xerophyllum tenax*) were used because they concentrate gold and molybdenum, respectively (Erdman *et al.* 1985). Results show that the molybdenum anomalies are peripheral to those of gold, demonstrating the zonation of the mineralization. This information has therefore assisted in both the selection of drill targets and helped in understanding the nature of the mineralization.

Similarly, work in Saskatchewan has shown that spruce bark can be of value in outlining arsenic distribution patterns, whereas alder twigs are generally deficient in arsenic, yet are enriched in molybdenum

(Dunn 1984). In this case, both media are efficient at concentrating gold, but by sampling the two species, a more comprehensive knowledge of the underlying mineralization can be obtained.

Ideally, of course, the sampling medium should provide chemical data that is as informative as possible. In some instances the advantage of collecting more than one sample type will be minimal, provided the sample medium available is sufficiently sensitive to the presence of those elements of interest. For example, a study was conducted over a zone of gold mineralization with associated arsenopyrite where the vegetation cover was primarily balsam fir. Twigs of this species are moderately effective at concentrating gold and arsenic. Samples from profiles across the zone of mineralization showed a strong positive response to the gold, and indicated a displaced zone of arsenic enrichment (Dunn 1986b). Not all studies, however, provide such satisfactory results. Over some auriferous zones with no overburden, the gold uptake by vegetation has been shown to be of low magnitude (Dunn 1983c; Fedikow 1986). Perhaps the organic acids of the soils and the bacterial decomposition of the fallen vegetation are required to enable gold to be taken up into a plant's root system. Clearly, there are many complicating factors which we are only just beginning to perceive.

Several studies on the seasonal variation in the metal content of various plant tissues have indicated that gold exhibits quite extreme concentrations. Stednick *et al.* (1987) found that in the mountains of Colorado the gold concentrations in pines were highest in spring and summer. However, in Saskatchewan, shrub alders contained far more gold in spring than summer (Dunn 1986c); moreover, a similar pattern was observed in several species growing over zones of gold mineralization at Hemlo, Ontario (Cohen *et al.* 1987).

It is apparent, therefore, that both environment and species dictate the optimum time for obtaining highest gold concentrations. This emphasizes the maxim in exploration biogeochemistry that a survey should be undertaken in as short a time as possible, in order to minimize the effects of seasonal changes.

Platinum Group Metals (PGM)

With the exception of a few analyses published by Fuchs and Rose (1974), the first biogeochemical studies directed toward the exploration for PGMs have been published only within the past few years. Kothny (1979) studied the distribution of palladium in oak and black walnut from California, and found more palladium in some plant ash than in the underlying soils. Another study recorded platinum concentrations in seventeen species ranging up to 43 ppb Pt (Kothny 1987). Riese and Arp (1986) collected twigs of lodgepole pine from over part of the Stillwater Complex, Montana, and found concentrations in ash of up to 11 000 ppb Pd and 4000 ppb

Pt, thereby demonstrating the potential value of plant analysis in helping to outline platinumiferous bedrock.

In the boreal forests, spruce twigs were shown to be the most appropriate sample medium, yielding up to 1350 ppb Pd and 880 ppb Pt in ash (Dunn 1986b). More recently, data have been obtained on the full suite of PGMs in vegetation ash, and it appears that there is no appreciable partitioning of PGMs in the process of transferral from the rocks through the root systems into the aerial parts of plants (Dunn *et al.*, in press).

The advent of the ICP/MS has permitted accurate determination of a few ppb each of platinum, palladium, and rhodium in as little as 1 g of ash, such that biogeochemistry has recently become a viable exploration method for PGMs. Previously, 5 to 10 g of ash was the minimum amount required for platinum and palladium analysis (for detection limits of about 10 and 5 ppb, respectively); this much ash required the collection of an impractically large sample of fresh vegetation.

BASE METALS

Whereas uranium and then precious metals have been the elements of greatest interest since the mid-1970s, exploration for base metals has been steadily progressing, and many biogeochemical studies have been directed toward these commodities. Further occurrences of the hyper-accumulation of nickel by a number of plants, mainly in the tropics, have been reported (e.g. Brooks *et al.* 1977; Wither and Brooks 1977; Reeves and Brooks 1983a; Dakshini *et al.* 1982). In southern Europe, the distribution of a variety of base metals in several common plant species, especially *Rumex* and *Minuartia*, has been examined (e.g. Kelepertsis and Andrulakis 1983; Kelepertsis *et al.* 1985; Reeves *et al.* 1986), and in Italy, Crisci *et al.* (1982) found a consistent lead-zinc-manganese association within proven sulphide mineralization.

A multi-element study of vegetation growing over porphyry-style mineralization in the temperate forest of northern Wales found that copper, molybdenum, and rubidium were enriched within spruce directly over the known mineralized zones (Al Ajely *et al.* 1985). Conversely, larch samples did not indicate the location of the mineralization.

In more northerly climates, a study of material from herbaria demonstrated the value of using archived samples in outlining metalliferous regions in Fennoscandia (Brooks *et al.* 1979). In Canada, Fedikow (1984, 1985) examined the distribution of some base metals and precious metals in the zone of glacial dispersion from a stratabound deposit in northern Manitoba and found that biogeochemical anomalies represented an exploration target larger than the zone of mineralization, and thereby demonstrated that the method can help in focusing exploration. A study in similar terrain in Ontario found

that the zinc content of some conifers and grasses effectively mapped a metalliferous glacial-dispersion train (DiLabio *et al.* 1982).

MERCURY

Of particular interest was the discovery that the amount of mercury retained in plant ash (probably as a mercury carbide) bears a distinct relationship to zones of mineralization (Kovalevskii 1986a). Table 33.3 summarizes some of these data and shows that, whereas background levels are less than 50 ppb Hg, enrichments over different types of mineralization in the Soviet Union range from 500 to 300 000 ppb Hg.

In Canada, Warren *et al.* (1983) analyzed over 1200 oven-dried plant samples and established that background levels were less than 15 ppb Hg, in contrast to levels of 300 to 1600 ppb Hg near a mineralized fault.

OTHER ELEMENTS

Baseline data are now available for most elements of the periodic table in a wide range of common species. Table 33.2 indicates alongside the reference those elements which are emphasized in the study. However, it is common for a large number of elements to be obtained from a comprehensive analytical program—Table 33.2 is not, therefore, comprehensive. Many studies of elements of lesser current economic interest are to be found in the Russian literature; e.g. Berzina *et al.* (1982) on boron, Kovalevskii (1978a) on beryllium, Talipov (1984) on tungsten, Talipov and Tverskaya (1984) on tungsten, tin, bismuth, and manganese. Elemental data of varying degrees of detail is now available, but it is frequently difficult to extract from the abundance of papers in a multitude of languages. This is inevitable for a complex science in its "formative years".

TABLE 33.3. MERCURY IN ASHED PLANT TISSUE (SIBERIAN DEPOSITS); AFTER KOVALEVSKII 1986A.

TYPE OF DEPOSIT	MERCURY CONCENTRATION (ppb)	
	BACKGROUND	OVER ORE
Gold	38	800
Silver	30	500
Iron	14	500
Tungsten	16	940
Molybdenum	40	3300
Antimony	54	2200
F, Be + Pyrite	50	2500
Polymetallic/Pyrite	33	4300
Mercury	33	300 000

LESS COMMON METHODS OF BIOGEOCHEMICAL EXPLORATION

AQUATIC MOSSES AND STREAM PEAT

Aquatic mosses and liverworts are types of bryophytes. Their chemistry has been studied from time to time over the past century, and their value to biogeochemical exploration has been assessed and documented by several researchers over the past twenty-five years, notably Hans Shacklette at the United States Geological Survey (Shacklette 1965a, 1965b). In a recent review it was noted that "the properties of aquatic bryophytes in trapping sediments, adsorption of metals..., concentrating metals, and their long life...make them, under certain conditions, the preferred sampling medium for prospecting" (Shacklette 1984).

Bryophytes have been used with varying degrees of success to explore for uranium in the northwestern United States (Shacklette and Erdman 1982), for gold and silver in Wales (Jones 1985), and for base metals in Alaska (Smith 1986). In Fennoscandia, regional geochemical surveys comprising the "Nordkalott Project" were carried out from 1980 to 1983 within an area of 250 000 km². Included as a prime sampling medium, were aquatic bryophytes (referred to in general as stream moss). Moss samples from 5475 sites were collected, analyzed for fourteen elements, and the data plotted as a series of maps (Geological Surveys of Finland, Norway, and Sweden 1986). It is apparent that elements in the stream mosses reflect the main geochemical provinces and lithological units, even at this low sample density. It was found, however, that the mosses provided element distribution patterns similar to other sample media (tills, stream sediments, and stream peats).

In general, the conclusion has been reached from several studies, that aquatic mosses can provide geochemical information of value to exploration, especially where there is a paucity of stream sediments.

PEATS AND FOREST LITTER

A second sample medium of the Nordkalott Project was that of stream bank peats, comprising mixtures of humic material, plant roots, and leaf litter, with varying inorganic content. This medium was investigated extensively prior to the onset of the Nordkalott Project by a pioneer of biogeochemistry, the late Nils Brundin, and his associates at the Geological Survey of Sweden (Brundin *et al.* 1987). This milestone study demonstrated that for much of Scandinavia stream bank peat is an effective and practical reconnaissance geochemical-sampling medium. An important discovery was that for roots of sedges and organic stream bank material, seasonal and annual variation in chemistry is correlated with the limonite content, which in turn is a function of the variation in precipitation. Consequently, it was recommended

that for this material, heavy metal concentrations should be normalized against the limonite content. However, for the aerial parts of plants this normalization may not be appropriate, because of the many physiological barrier mechanisms to element uptake that occur.

Studies of the use of humic substances in exploration fall under a variety of names, including 'peat', 'humus', and 'bog'. In Wales copper-rich bogs were studied (Andrews and Fuge 1986), and in California detailed studies of a uraniferous bog led to the conclusion that humic substances, rather than living plant material, were responsible for uranium entrapment (Idiz *et al.* 1986). Studies of gold and other elements in humus were made at several localities in Canada and provided a wealth of valuable data (Fortescue 1985, 1986). Gleeson *et al.* (1986) found gold anomalies in near-surface peat in bogs resting on glaciolacustrine sediments in Ontario, and among their explanations they invoked a possible electrogeochemical mechanism for the metal concentrations. Toverud (1979) demonstrated that, in Sweden, humus can be useful in tungsten prospecting on a local scale.

A valuable study in Finland demonstrated that there is appreciable seasonal variation in humus chemistry (Salminen and Kakkola 1984); therefore, as with other organic media, a sampling program should be completed within a period of a few weeks in order to minimize these seasonal fluctuations.

Forest litter has been used quite extensively by exploration companies seeking gold in Canada; however, there have been few published case histories. Dunn (1986a) showed that in an area of eastern Saskatchewan, gold, arsenic, and antimony were more enriched in forest litter than live vegetation. The potential problem with forest litter, however, is that its composition varies considerably from one sample site to the next; whereas at one site a sample of decaying deciduous leaves may be obtained, at another it may be conifer needles or trunkwood. Since the chemistry of these live tissues is different, there is the danger in forest litter surveys of trying to compare samples of totally different composition. Notwithstanding these limitations, information of value for mineral exploration can be obtained from forest litter.

GEOZOOLOGICAL METHODS

The chemistry of the Animal Kingdom is one step further removed from bedrock mineralogy than that of the Plant Kingdom, but even so, animals can provide clues that may lead to the discovery of mineralization. The various creatures that have been used to assist the prospector are discussed in Brooks (1983a, 1983b). Birds, dogs, fish, termites, and, more recently, bees are the creatures that have proved the most practical and informative for mineral exploration. Since bees rarely forage far from their hive, the

pollen that they collect reflects the average concentrations of trace elements in flowers within a 2 km radius from a hive. By establishing a network of hives and collecting the pollen, it is possible to determine those areas with relative enrichments of metals (Warren 1980; Warren and Horsky 1982).

PLANT SAPS

A few investigations have been made of the value of plant saps to exploration. Birch sap analyses from trees growing over a stockwork of intermediate volcanics in Siberia successfully delineated zones of zinc and gold mineralization (Krendeliev and Pogrebnyak 1979). Zaguzin *et al.* (1981) tested the same medium over a zone of tungsten and molybdenum mineralization and concluded that "the method offers greatest promise in areas with covered litho-geochemical aureoles and absence of groundwater discharges".

Studies recently commenced at the Geological Survey of Canada are determining the trace metal content of sugar maple sap, and assessing the response to differing substrate composition.

GEOBOTANICAL METHODS

Relatively few papers have been published over the past decade that deal specifically with geobotanical studies (i.e. the recognition of plants or plant communities characteristic of a particular type of mineralization). Many papers touch upon this subject, but commonly deal primarily with the biogeochemical approach. Geobotany has achieved greatest success in the tropics. In South-West Africa and Botswana, Cole and Le Roex (1978) identified a number of plant communities that led to the discovery of copper deposits beneath as much as 30 m of calcrete. Another paper (Cole 1980) outlined the geobotanical expression of differing deposits in several parts of the world.

A valuable compilation by Brooks (1979b) examined the role of indicator plants in geobotanical methods of mineral exploration, and noted that over a third of all indicator plants belong to the mint, pea, and pink families.

Other comprehensive geobotanical studies of particular value are those by Brooks (1983a, 1987), and Brooks and Malaisse (1985).

MICROBIOLOGY IN EXPLORATION

Two basic microbiological methods of exploration are being developed. The first involves population counts of spores of the common soil bacterium *Bacillus cereus* (Parduhn and Watterson 1984; Watterson 1985; Watterson *et al.* 1986; Parduhn 1987). It has been found that *B. cereus* populations are commonly higher in soils over zones of metal enrichment than over background areas. The bacteria have a resistance to antibiotics such as penicillin (produced

by fungi) and heavy metals in soils. It appears that the bacterium probably steals a water molecule from the penicillin, leaving a gap in the penicillin structure and providing room for a heavy metal ion to be trapped before it can hurt the bacterium. Hence, simply by sampling soils, extracting and counting the bacteria, areas of bacterial (hence metal) enrichment can be identified. A study by Parduhn *et al.* (1985) over four buried gold deposits in the western United States, noted elevated spore populations over the mineralized zones.

Bacterial populations vary considerably with environment, and also with season. The method is particularly well suited to arid environments, but the normally high concentrations beneath the boreal forest render the technique more complicated in northern climes.

The second method involves the measurement of metal tolerances of the total bacterial population by means of culture techniques (Michaels and Riese 1986a, 1986b). Luminometry is used to measure the amount of light generated by adenosine triphosphate (ATP) enzyme reaction after exposure of the bacteria to either the metal being sought after or its pathfinder elements. At the present time modified methods that show promise for assisting in the exploration for both minerals and hydrocarbons are being developed (G. Michaels, Professor, Western State College, Gunnison, Colorado, personal communication, 1987).

CONCLUSIONS

The wealth of information on biogeochemical methods of exploration is proliferating. The exploration industry has discovered most of the world's obvious deposits, and must therefore seek new and subtle indications of mineralization. In view of the vast areas of the world that are covered by forest and/or exotic overburden, the analysis of vegetation is a logical step toward the discovery of mineral deposits. Now that analytical technology has developed to the point that accurate analyses can be made of trace amounts of elements in biological materials, biogeochemistry is entering a new era of development. Studies in the past decade have assisted in refining the methodology to be applied in an exploration program using vegetation, and a greatly expanded data base is available against which new analytical data may be evaluated. The increasing volume of successful case histories bears witness to the value of biological methods in helping to discover economic deposits of minerals. It is of great importance to note, however, that these successes are largely a result of the greater attention that is now being paid to sampling the correct plant organs in the proper manner, and taking into consideration the time of year that the collection is made. In other words, there is much better understanding of the limitations of biogeochemical methodology. As with any aspect

of science, properly trained personnel are required to achieve success.

Microbiological methods promise to be yet another approach of value to an exploration program. Similarly, geozoological studies have their niche for exploring certain environments.

We have seen extensive application of remote-sensing techniques to exploration over the past decade. There remains the need for much greater 'ground-truthing' of the subtle images obtained from satellite and airborne sensors—this is the realm of geobotany and biogeochemistry, and is an area of considerable intensity of effort at this time.

Requirements for the next decade include:

1. A greatly expanded data base, summarizing background concentrations of many elements in easily sampled tissues of many common plant species. Without such a "yardstick" the exploration community will be unable to assess the significance of biogeochemical data obtained. Note should be made of important modifications to element concentrations brought about by differing environmental conditions; for example, is gold uptake by spruce twigs similar in well-drained ground to that encountered in spruce bogs?
2. Continued attention must be paid to "ground-truthing" (especially vegetation analysis) of remotely sensed data (both airborne and satellite).
3. We need to investigate the value of biogeochemistry as a reconnaissance-level exploration tool. The technique has the potential for delineating major metallogenic "provinces", both rapidly and economically. We now know that many metals have a tendency to migrate to the extremities of trees, so that in rugged and heavily forested terrains a helicopter survey to collect tree tops may prove a viable method for screening barren from metalliferous areas.
4. Closer examination should be given to the processes that control metal uptake, translocation, and fixation. Scanning electron microscope studies of cell structures, and crystal growth in and on these cells may assist in our understanding of these processes. To date, the only crystals identified by the author are calcium oxalate (and possibly aragonite); however, Russian scientists claim to have discovered authigenic crystals of ore-forming minerals (e.g. galena, sphalerite, cobaltite) in plant structures (Kovalevskii, Biochemist, Ulan-Ude, Siberia, personal communication, 1984).
5. More microbiological studies are required to determine the specificity of bacterial populations to ore-forming elements. The question remains with respect to gold: are the increased populations really attributable to the presence of gold, or to an associated trace metal, or even simply to the presence of sulphides or iron?

6. Perhaps instrumentation could be developed for sampling organometallic exudates from the forest, and determining (no doubt at the parts per trillion level) trace metals associated with these complexes. Just by walking through the forest on a fine summer's day, the nose can readily pick up a variety of mainly terpene-related aromas (in the northern forests) that emanate from the vegetation. Are variations in their chemistry sufficient to warrant the development of "gas biogeochemistry" as an exploration method?
7. Finally, we need a wealth of case history studies against which to evaluate newly acquired data sets. Studies should be made over various styles of mineralization. Clearly, the biogeochemical response of gold associated with disseminated arsenopyrite will be different from that of a quartz-hosted gold deposit associated with molybdenite.

Biogeochemistry is 'coming of age' and gaining increasing respectability as a science of value to the exploration community. An enormous amount of work needs to be done to refine methods and unravel the many complex interacting processes. The science is not yet exact.

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34. Multi-Element Geochemical Domains—An Aid to Exploration

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ABSTRACT

Numerous reconnaissance geochemical surveys (lake and stream sediments) have been carried out by the Québec Ministry of Energy and Resources. These cover large portions of the Appalachian, Grenville, Churchill, and Archean geological provinces.

From these surveys, it is possible to distinguish geochemical regions characterized by:

- specific background values
- dominant element associations
- specific geochemical "texture"
- very large areas

These are referred to as "geochemical domains".

Where adequate geological data exist, "geochemical domains" can generally be correlated to bedrock composition. Geochemical domains can thus be considered as an important tool to assist geological mapping in its initial stages by suggesting geochemically distinct units, chemical discrepancies (facies)...

Samples gathered from each of these geochemical domains should be considered as subpopulations for which statistical techniques yield more cohesive results.

INTRODUCTION

Since 1965, numerous reconnaissance stream sediment and lake sediment surveys have been carried out by the Québec Ministry of Energy and Resources, SOQUEM, and The Société de Développement de la Baie James. The parts of these surveys considered here, cover large portions of the Appalachian, Grenville, Archean, and Churchill Provinces, as well as the Labrador Trough (Figure 34.1). Over 100 000 samples are considered, covering close to 400 000 km². The data is presented in more than 23 different publications.

The present work aims to, summarize several observations which can be drawn from this data, suggest basic concerns for consideration prior to conducting geochemical surveys, and provide a means to enhance the significance of geochemical anomalies.

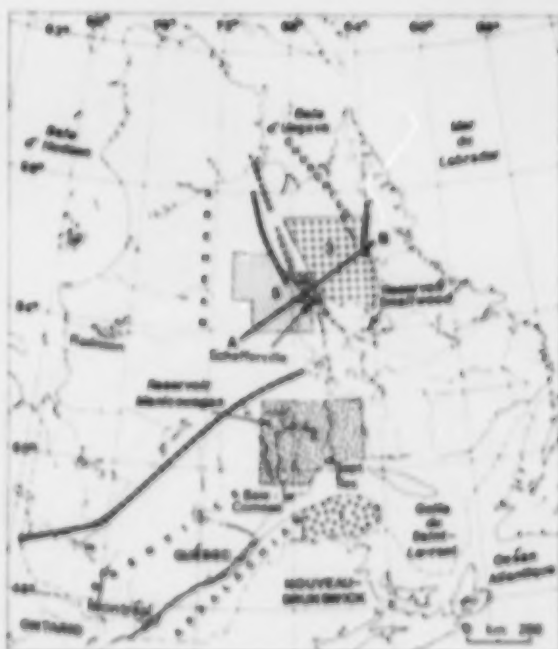


Figure 34.1. Location of study area.

SAMPLING AND CONTROLS

The surveys were conducted according to standard geochemical surveying methods. The stream sediments were collected in the Appalachian Province at a 500 m spacing between sample sites, thus yielding 2.5 samples per km². Lake sediment surveys were undertaken in the other area at a sample density varying from 1 sample per 2.5 km² to 1 per 13 km². Sample densities were adjusted so as to optimize resolution with regards to the level of knowledge of the bedrock geology. Thus, in areas where geological mapping was conducted at a 1:10 000 or 1:50 000 scale, the sample density was 1 sample per 2.5 km² (see survey 4 on Figure 34.1). On the other hand, the sample density was 1 sample per 13 km² where the geology was mapped at a 1:500 000 scale (see surveys 2, 3, and 5 on Figure 34.1).

Quality control was assured either by traverse verifications, i.e. resampling, as well as the introduction of control reference samples at a six percent

frequency, which aimed to assure coherence of analytical data as well as consistency on a year to year basis.

Although analytical techniques have been evolving since the late sixties, test comparisons between techniques leads to calibration and coherence.

AVERAGE CONCENTRATION

Average values for copper, zinc, and cobalt concentrations derived from the 76 000 stream sediments as well as the 25 000 lake sediments, generally approach normal crustal whole rock abundances (Table 34.1).

Discrepancies from whole rock values can be explained by the type of samples involved (sediments rather than rocks), as well as the type of analysis (partial extraction rather than total metal content).

Closer examination of surveys originating from distinct geological provinces shows drastic differences (Table 34.2). For example, average zinc content is 58 ppm in the Grenville Province, whereas in the Labrador Trough it attains 137 ppm. However, no similar variations can be observed for cobalt.

It can be seen that geological provinces may have, for given elements, respective regional geo-

chemical backgrounds or reliefs. Thus variations from one geological province to another may be so drastic that anomalies observed locally in the catchment basins related to a given geological province may disappear when data are pooled with those of another adjacent province.

For example, it can be seen on Figure 34.2 that arsenic anomalies in lake sediments derived from gold- and arsenopyrite-bearing Archean rocks from the Wawakus Lake area (Bélanger 1987) are attenuated with respect to data from the Labrador Trough. On the other hand, it becomes most difficult to differentiate arsenic anomalies within the Labrador Trough.

TABLE 34.1: COMPARISON BETWEEN AVERAGE CONCENTRATION OBSERVED IN STREAM SEDIMENT, LAKE SEDIMENT AND WHOLE ROCK (ppm) ANALYSIS.

	Cu	Zn	Co
crustal abundance *	68	76	29
stream sediments (a) **	17	50	13
lake sediments **	41	101	12

* whole rock analysis (Renov and Yaroslavsky 1972)

** hot extractable metal

(a) Choinière 1985

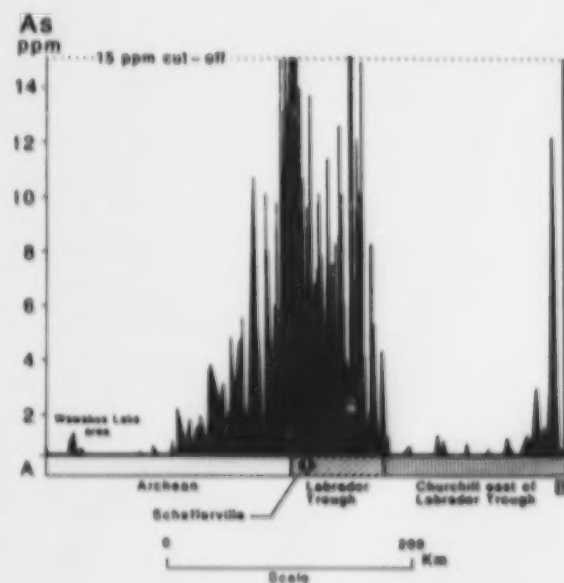


Figure 34.2. Arsenic profile based on regional lake sediment survey data.

TABLE 34.2: COMPARISON BETWEEN AVERAGE CONCENTRATIONS (ppm) OBSERVED IN LAKE SEDIMENT SURVEYS ORIGINATING FROM DIFFERENT GEOLOGICAL PROVINCES.

GEOLOGICAL PROVINCE	ELEMENT	Cu	Zn	Co	NUMBER OF SAMPLES
Grenville	(1)	25	53	13	6200
Archean	(2)	38	81	13	3800
Churchill	(3)				
(east of Labrador Trough)		52	55	11	4800
Labrador Trough	(4)	53	137	13	11000

(1) Choinière 1987

(2) Beaumier 1986a

(3) Beaumier 1983, 1984

(4) Beaumier 1986b, in preparation

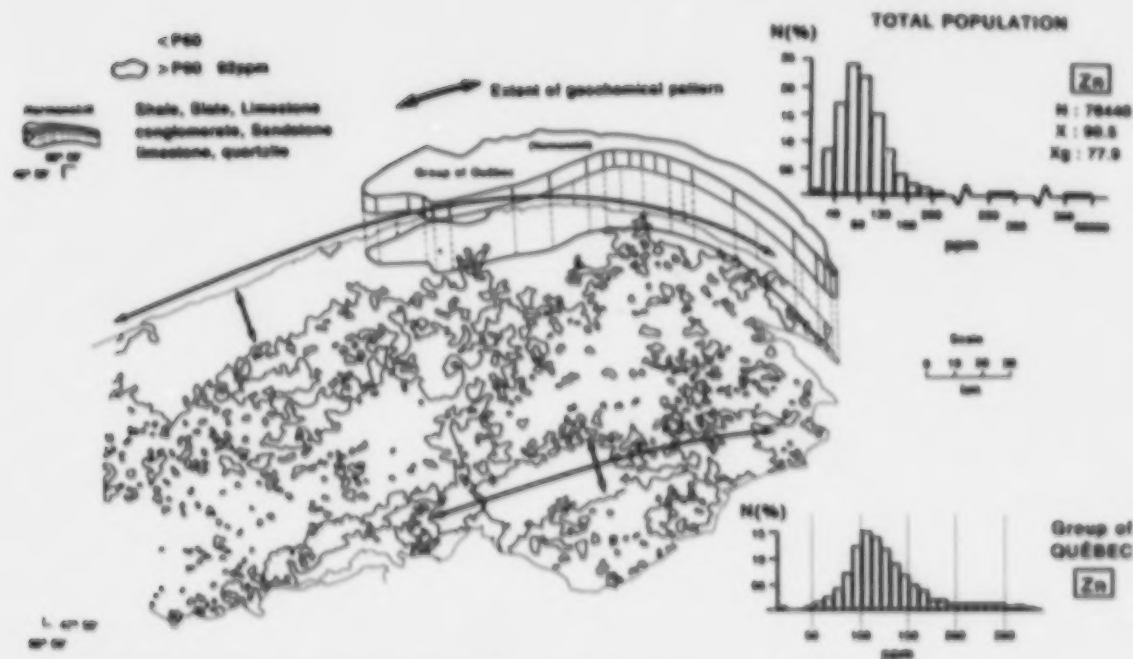


Figure 34.3. Zinc distribution in stream sediments from the Gaspé area.

Any statistical analysis would place very little importance on this anomaly either because of the wide contrast in the concentration and/or because of the small number of samples involved. The problem is not in the use of one statistical technique rather than another, but to identify which population of samples should be subjected to statistical analysis.

Similar variations exist for most elements, but not necessarily for all (see Cobalt in Table 34.2). Thus, it appears that geological provinces often have characteristic background values for given elements and that interpretation of any sample population should be based on samples from a single geological province.

The level of background values is not the only characteristic of geochemical provinces. Comparison of the zinc data for stream sediments in the Appalachian Province (Figure 34.3) with that of lake sediments in the Grenville Province (Figure 34.4) and in the Churchill Province (Figure 34.5), shows clearly the differences in "texture" (length, width, continuity, linearity) characterizing the different provinces.

One can observe that relatively "higher values" in the zinc distribution from the Appalachian Province group together in continuous, linear wide bands (see Figure 34.3), whereas in the Grenville Province, the lake sediment survey yields narrow, sinuous, and more discontinuous bands. Considering the strong metamorphism present in the Grenvillian rocks (amphibolite and granulite facies) as well as

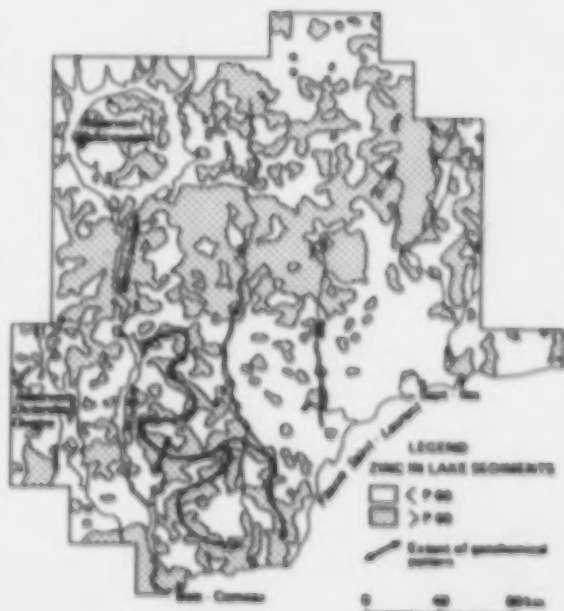


Figure 34.4. Zinc distribution in lake sediments from the Manicouagan area.

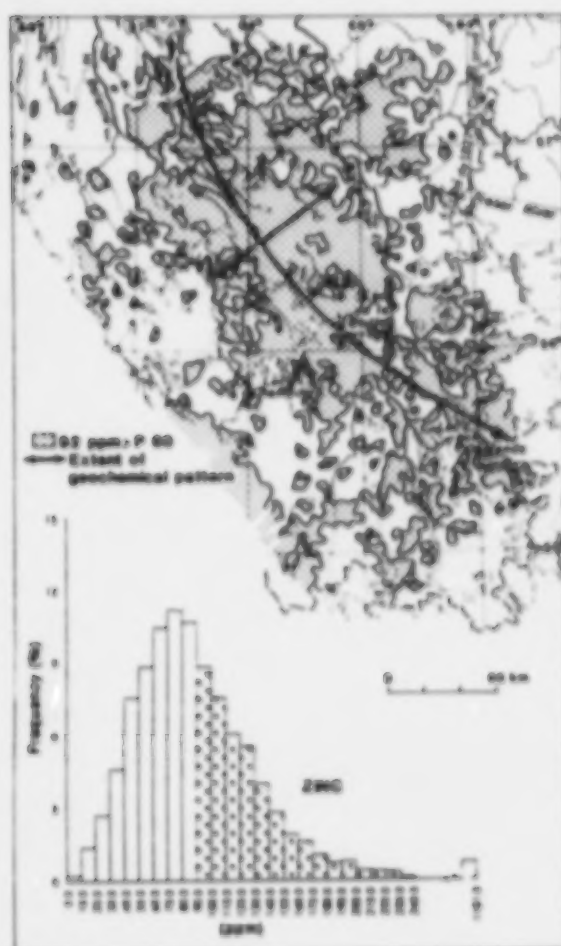


Figure 34.5. Zinc distribution in lake sediments from the Rivière George area.

the multiphase tectonism, both producing a most heterogeneous bedrock composition, it is not surprising to observe more sporadic results in the secondary environment. Wet base glaciation may also be an important cause of the more sporadic results. This type of glaciation favours glacial transport, dispersion, and dilution of metals, thus producing a more irregular and patchy texture.

The variation in "texture" of geochemical data observed between the Appalachian and the Grenville Provinces is not necessarily due to the difference in the type of sampling (stream sediments versus lake sediments). If such was the case, all lake sediment surveys would show a similar irregular "texture". Examination of the geochemical lake sediment data from the Churchill Province located east of the Labrador Trough (see Figure 34.5) shows a "texture" similar to that observed in the Appalachian stream sediment data.

Thus "texture" of the geochemical data is a characteristic of geochemical provinces. It is directly related to the width, continuity ... and geochemical contrast of different geological features (lithological, glacial...).

FORMATIONAL ANOMALIES

The width and continuity observed in the stream sediment data from the Appalachian province (Gaspé area) are intimately correlated with geological units (Choinière 1985). Calculation of the distribution, average concentration, threshold values... for samples gathered over a given geological unit (see Group de Québec, Figure 34.3) have been referred to as "formational anomalies" (Choinière 1982).

"Formational anomalies" refer to a specific distribution of values which characterize a given population of samples reflecting a specific geological unit. To establish such subpopulations some authors have mechanically subdivided the total population of samples by polygons covering geological units, discarding samples reflecting a mixture of geological units. Others have systematically coded bedrock geology according to the prime source unit in each catchment basin.

Each subpopulation produced is characterized by a given average, standard deviation, frequency distribution curve, skewness... (Figure 34.6) and can then be used as a reference population from which it is possible to calculate background, threshold, and anomalous values.

Considering the fact that more than 50 percent of the province of Québec still requires basic reconnaissance geological mapping, as well as the heterogeneity of the bedrock in certain geological provinces, it can be deduced that formational anomalies cannot be systematically established, such as in the Gaspé area.

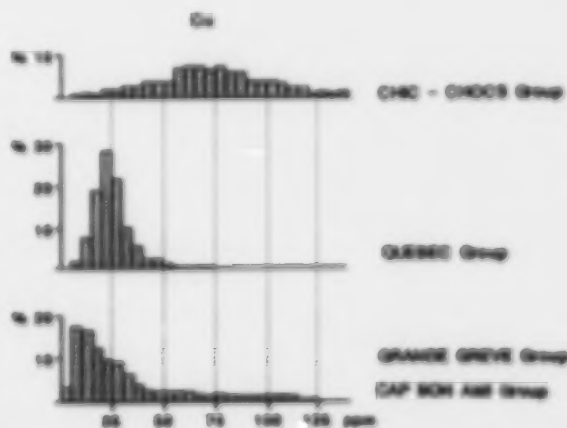


Figure 34.6. Frequency distributions of Cu in stream sediments.

GEOCHEMICAL DOMAINS

Within each geological province one can observe either narrow discontinuous patterns (see Figure 34.4) or wide continuous patterns (see Figure 34.3 or (Figure 34.5) which represent subpopulations of spatially correlated samples showing a distinct contrast (higher or lower values) in the distribution of data for different elements (later referred to as domains). The size of these is most variable. Some have been shown to be greater than 25 000 km² (Beaumier 1986a), others are relatively small. To distinguish the latter from sporadic geochemical anomalies, we have considered a cutoff size of approximately 75 to 100 km².

Although this cutoff is somewhat arbitrary, when dealing with a regional lake sediment survey such a cutoff screens out two or three adjacent sample site anomalies from much larger trends. The domains (Figure 34.7) are themselves approximations of the distribution of data (see Figure 34.5). Some authors

have used moving averages to smooth and to clarify similar geochemical patterns (Armour-Brown and Nichol 1970). Geochemical domains are generally correlated with geological "features" which still need to be defined, they are not "formational anomalies".

Mapping of these domains will eventually lead to the recognition of the source geological "features" as well as the definition of subpopulations of samples most appropriate for any statistical evaluation.

STATISTICAL IMPLICATIONS

Dividing the overall population into subpopulations according to geochemical domains will result in important changes in the statistical behaviour of data (average, standard deviation ...). Significant correlation coefficients (R values) can also be drastically different from one domain to another.

As one can observe on Table 34.3, element association characterized on the total population (i.e. R(Zn-Cd) = +.31) can change to either R = +.16 or R = +.63 depending on which geochemical domain is considered. Similar enhancements of element association will occur for all elements characterizing the given geochemical domain. Elements not involved in the characterization of the domain (i.e. Cu on Table 34.3) do not show any change in correlation coefficient.

Such important variations in correlation coefficients will influence multivariate statistics.

MULTI-ELEMENT GEOCHEMICAL DOMAINS

A multi-element approach will generate numerous domains showing specific element associations. Regrouping only two elements may yield numerous domains. For example, zinc (see Figure 34.7) in lake sediments east of the Labrador Trough combined with strontium produce five distinct multi-element geochemical domains depending on whether we deal with higher or lower strontium values associated with higher or lower zinc values (Figure 34.8).

Although in this example, two elements yield five multi-element domains, there is not a straight-

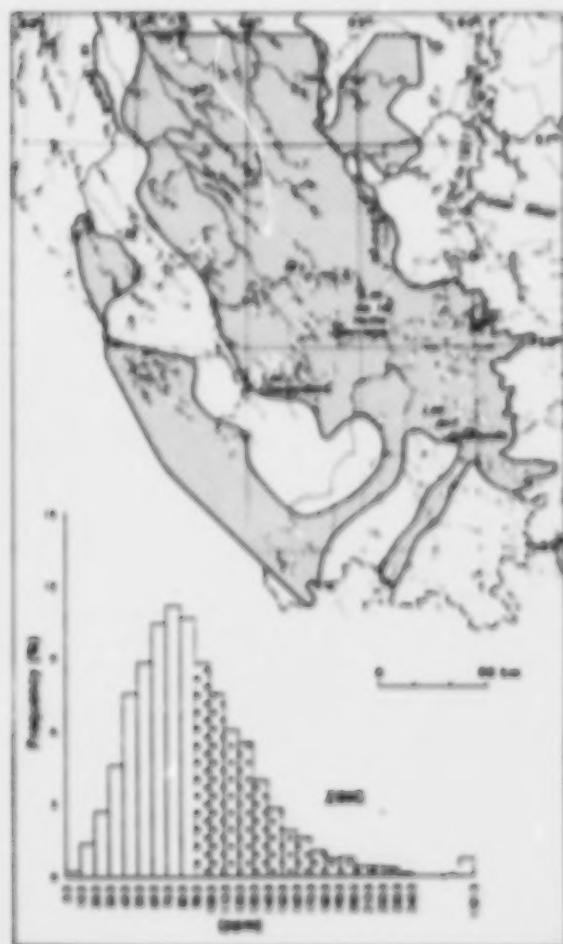


Figure 34.7. Zinc geochemical domain map.

TABLE 34.3: CORRELATION COEFFICIENTS (LOG VALUES) FOR LAKE SEDIMENT SUBPOPULATIONS, CANIAPISCAU AREA (WEST OF SCHEFFERVILLE).

	Domain low As (n: 3512)	Total population (n: 3608)	Domain high As (n: 316)
As - Zn	.26	.38	.60
As - Cd	.15	.42	.61
Zn - Cd	.16	.31	.63
Zn - Hg	.25	.50	.61
As - Cu	.32	.39	.53
Cu - Zn	.63	.40	.64

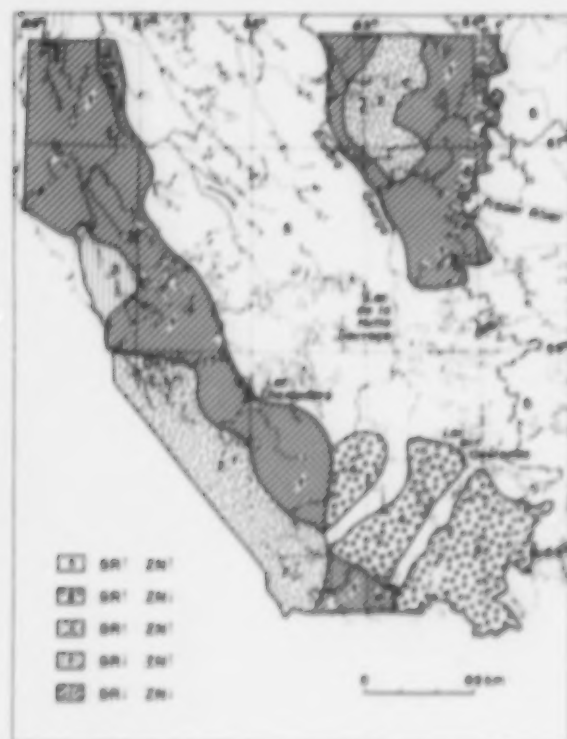


Figure 34.8. Combined zinc and strontium geochemical domains.

forward mathematical relationship. Numerous elements exhibit exactly the same spatial distribution, and thus do not multiply the number of domains. In other cases, specific elements do not define any geochemical domains.

Clear presentation of numerous multi-element domains can be facilitated by numbering the domains and representing their extent, together with an appropriate legend (Figure 34.9). Spatial relationships between domains (crosscutting, zoning...) combined with characteristic element associations (Sr, Mo, Ti, Cr, Ni...) become essential features from which lithological as well as chronological relationships may be interpreted.

Examination of the accompanying legend (see Figure 34.9) shows how 17 geochemical domains have been identified in the Caniapiscau area on the basis of the regional lake sediments survey data. Characteristics of these may vary from a single element showing (e.g. #15 on Figure 34.9) to a multi-element association (e.g. domain #9 on Figure 34.9). Some show discrete differences suggesting facies (e.g. domains 13a and 13b on Figure 34.9) while others may combine distinctly high values associated with extremely low values (e.g. domains #4 and #6 on Figure 34.9). Finally, extremely large do-

main embracing numerous smaller ones were identified as a series of domains (e.g. uraniferous series).

It was observed that ambiguous definitions of the lateral extent of each mono-element domain can be readily verified by the examination of other elements. Although low values have generally been considered to have little importance in exploration geochemistry, these have proven to be most useful in helping to define geochemical domains.

IMPLICATION FOR EXPLORATION

As geochemical domains are related to geological features, the mapping of geochemical domains (see Figure 34.9) can lead to the preparation of "pseudo-geological" maps which can be a basic tool in areas where the bedrock geology is not well known. These maps also permit the subdivision of regional survey data according to subregions which approach single population distributions. It is more effective to apply statistical packages to these single populations in order to identify anomalous levels, characteristic element associations, as well as reduce the size of the target areas.

For example, the regional lake sediment arsenic anomaly of approximately 7500 km² just west of the Schefferville area should actually be considered as a geochemical domain (see south part of domain 10 on Figure 34.9). This domain is characterized by an arsenic content of 2.4 ppm and a standard deviation of 1.6 (Figure 34.10). The threshold level with respect to this given geochemical domain is considered to be 3.0 ppm (84th percentile) rather than 1.8 ppm (84th percentile) when considering the total population. This results in a reduction of the anomalous area to less than 500 km². Twenty-nine new gold showings have been found in this area, all of which are clearly related to the 3.0 ppm arsenic anomalous level (see Figure 34.10).

Although arsenopyrite prevails in the area, the mineralizations seem related exclusively with loellingite (FeAs₂) which is, according to Bélanger (1987):

"concentrated in or near silicified beds of metabasite and iron formations which are composed mainly of amphibole, garnet, magnetite and locally ilmenite."

The identification of a high arsenic geochemical domain implies the existence of a low arsenic domain. If we consider the latter as a distinct sub-population, the threshold drops drastically. At an equivalent 84th percentile threshold level (1.3 ppm) an area of close to 300 km² is identified as a target arsenic anomaly (Figure 34.11). The area (Wawakus Lake) is located between Lake Caniapiscau and Lake Clarendon, approximately 150 km west of Schefferville (see Figure 34.2).

Such an anomaly would not have been of much interest whatever means may have been used for its identification. All proportions kept, this anomaly could be considered as important as the one shown on Figure 34.11. Four out of six grab samples col-

GEOCHEMICAL DOMAIN		
	Characteristic elements	Remarks
10	U	Extremely high
10	Sr, Mo	
10a	Sm, Ce, La, Eu, Th	Zonation
10b	Sm, Ce, La, Eu, Th, Ca	High calcium
10c	Sm, Ce, La, Eu, Th, Mo	Presence of molybdenum
10	Cr, As	Elongated form
11	Sm, Ce, Y, Mo	
NON URANIFEROUS SERIES (LOW URANIUM BACKGROUND)		
10	Zn, As, Cd, Ni, Hg	Probably associated with mineralization
9	Ti, CR, Ni, Mg, Zn, Pb, Mo	Zonation with 10, 9, 8, 7
9	Ti, CR, Ni	Facies association
7	Background	No characteristic element
9	Eu, La (high) with Co, K, Sr (low), As, (moderately high)	Elongated form in the N.W. sector of the map
9	Eu, La (high) with Co, K, Sr (low)	Elongated form in the N.W. sector of the map
9	Eu, Cr, La, Sr (high) with Co, K (low)	Elongated form in the N.W. sector of the map
NON URANIFEROUS SERIES (LOW URANIUM BACKGROUND)		
9	U, Ti, CR, Ni, Mg, Zn, Pb, Mo	Higher uranium background but not extremely high
9	U, Ti, CR, Ni	Higher uranium background but not extremely high
1	U	Higher uranium background but not extremely high

CONCLUSIONS

These domains permit the subdivision of regional survey data into subpopulations from which

Geochemical domains can be mapped, and thus produce "pseudogeological" maps which represent geological "features" (not necessarily bedrock geology). These may be very useful in guiding geological mapping in it's initial stages. The mapping of geochemical domains should be considered an important activity for it is a major tool in orienting detailed geochemical surveys, supplying reference to element associations, as well as to relative anomalous levels.... all basic information to exploration geochemical surveys.

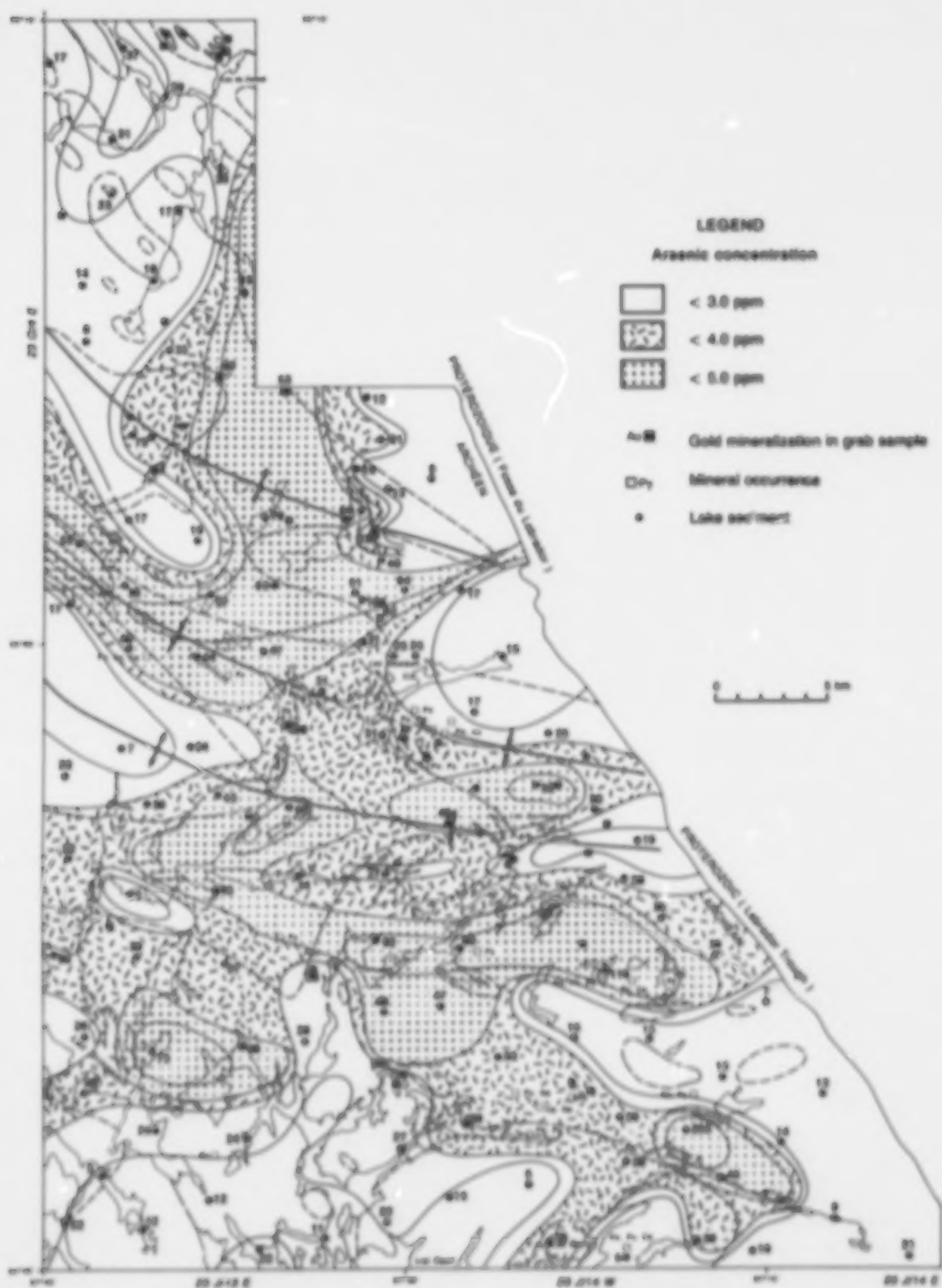


Figure 34.10. Arsenic in lake sediments from the high arsenic domain west of Schefferville.

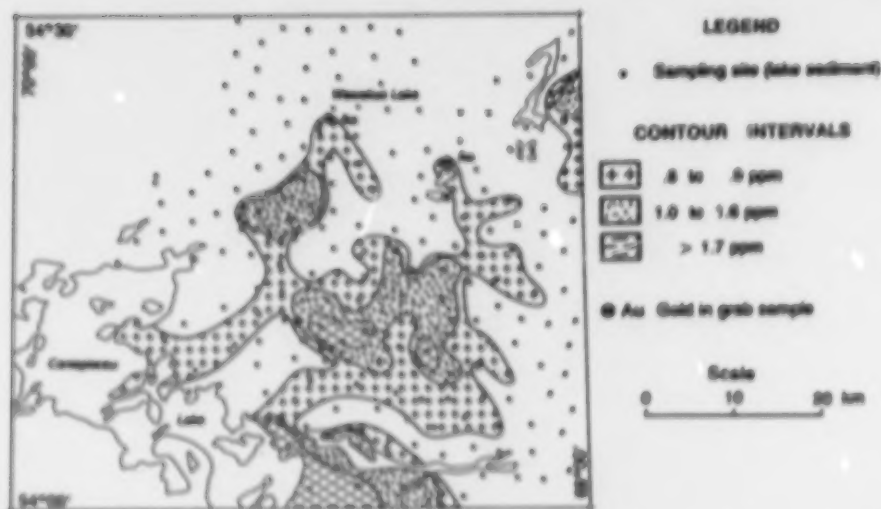


Figure 34.11. Arsenic in lake sediments from the low arsenic domain from the Wawakus Lake area (see Figure 34.2).

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35. Fluid Inclusion Gases in Gold Exploration

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ABSTRACT

Fluid inclusion gas analyses, commonly for H_2O , CO_2 , CO , H_2 , N_2 , H_2S , CH_4 and higher hydrocarbon gases, can be used to delineate gas haloes surrounding ore zones, as well as to reconstruct hydrostatic gradients in hydrothermal gold deposits. Although semi-quantitative Raman spectroscopic gas analyses can be carried out without destroying the inclusions, most gas analyses require that the inclusions be opened by crushing, thermal decrepitation, or laser ablation. Gases liberated by these methods are usually analyzed by gas chromatography or mass spectrometry, with sample size ranging from 5 g to individual inclusions. Present methods of analysis and interpretation are not standardized and care must be taken not to introduce spurious anomalies with the analytical process.

Preliminary analytical results for several types of gold deposits suggest that fluid inclusion gases exhibit compositional gradients that could be used in exploration. Fluid inclusions in vein quartz overlying ore shoots in epithermal systems are enriched in CO_2 and H_2S , possibly related to boiling of the ore fluid. Gas pressures estimated from analyses of boiling fluid inclusions at various levels in epithermal veins permit reconstruction of pressure gradients and prediction of ore shoot depths in unexplored veins. Acid-sulphate deposits exhibit peripheral CO_2 enrichment, also thought to be related to boiling, and greenstone gold deposits exhibit centrally located CO_2 anomalies that could indicate unmixing of CO_2 -rich mineralizing solutions. Sediment-hosted micron gold deposits are enriched in CO_2 but contain lower values in the central part of individual systems. Whereas the use of gas analyses to determine pressure gradients and depths in concealed ore shoots appears to be robust enough to be used as a primary exploration tool, most of the other gas patterns are relatively subtle and should be used in conjunction with other exploration guides.

INTRODUCTION

Fluid inclusions, which are common in all types of hydrothermal ore deposits (Roedder 1984), have provided critically important data for development of the models that guide modern mineral exploration (Roedder 1977). Recent efforts to use fluid inclusions more directly in exploration, especially for gold deposits, have involved analysis of the gas content of the inclusions in an effort to:

1. reconstruct the hydrodynamic environments in which the deposit formed
2. delineate chemical haloes surrounding ore zones or shoots

Interest has focused on the gas content of the inclusions because they provide information on the chemical state of the fluid and because fluid inclusions can be more widely distributed than precious metal values in some gold deposits. The following review discusses methods of analyzing the gas content of fluid inclusions, as well as some of the results that have been obtained for each of the more important gold deposit types or models.

It should be kept in mind in reading this review that there are many complications inherent in working with fluid inclusions. Chief among these is the problem of determining the relative ages of fluid inclusions and mineralization, which involves the identification of primary, pseudosecondary, and secondary fluid inclusions (Roedder 1984). This problem is particularly acute in hydrothermal deposits, where numerous pulses of hydrothermal activity and mineral deposition take place, but only some of these pulses deposit ore minerals (Casadevall and Ohmoto 1977; Kamilli and Ohmoto 1977; Vikre 1985). Even where a fluid inclusion can be related clearly to a specific stage of mineralization, the possibility exists that its contents have been changed by later processes (Roedder 1984; Bodnar *et al.* 1985). As explained below, the analysis of fluid inclusion gases is also a difficult task, involving the possibility of significant error at several stages.

ANALYSIS OF GASES IN FLUID INCLUSIONS

By convention, the so-called "gas content" of fluid inclusions includes most of the volatile constituents in the liquid and vapor phases of the inclusion. Accordingly, the most common gas is usually H_2O , followed by CO_2 , N_2 , CH_4 , and H_2S in approximate order of decreasing abundance. Numerous other volatile phases, including H_2 , CO , alkane and alkene hydrocarbons, He , NO_2 , COS , NH_3 , HCl , COS , CS_2 , and SO_2 , have been observed in fluid inclusions although, as discussed below, it is unclear whether some of these gases are formed by the analytical procedure (Norman and Sawkins 1987). Any type of analytical tool that will measure gas abundance can be used to analyse fluid inclusion gases. The most common of these methods are gas chromatography, mass spectrometry, and Raman spectrometry (Chellita *et al.* 1983). Capacitance

manometry, a technique involving estimation of gas abundances from measurements of gas pressures at various temperatures, has also been used (Sommer *et al.* 1985). Only Raman spectroscopy can be used in a non-destructive mode; all of the other methods require that the fluid inclusion(s) be opened and the gases released before analysis. Raman spectroscopy has been used to analyse CO_2 , CO, CH_4 , N_2 , as well as other gases and ions in fluid inclusions, but provides largely semi-quantitative information (Dhamelincourt *et al.* 1979; Rosasco and Roedder 1979; Dubessy *et al.* 1982; Wopenka and Pasteris 1986; Pasteris *et al.* 1986). More quantitative data, particularly on gases present in amounts of less than about one mole percent, which includes most gases other than CO_2 and H_2O , must be obtained by gas chromatography or mass spectrometry, which require that the fluid inclusions be opened and the gases released.

The two commonly used methods of releasing fluid inclusion gases for analysis are crushing and thermal decrepitation. Decrepitation (Smith and Peach 1949; Burlinson *et al.* 1983; Pashkov 1982; Mel'nikov 1983) has been used to estimate depositional temperatures and to guide exploration, although interpretations are complicated by multiple stages of inclusions and the fact that decrepitation requires that inclusions be heated above their homogenization temperatures, with the degree of overheating being inversely related to inclusion size (Leroy 1979). Where decrepitation is used to release gases for actual gas analysis, it is common to measure the homogenization temperature of the fluid inclusion(s) of interest separately and to test for the appropriate temperature interval at which to collect gases for analysis by step-heating (Figure 35.1). Crushing (Andrews *et al.* 1984) can be done at any temperature, including a previously measured homogenization temperature. Individual fluid inclusions can also be opened by laser ablation (Sommer *et al.* 1985). Release of gases from fluid inclusions involves complications including:

1. adsorption of inclusion gases onto newly formed surfaces
2. changes of inclusion gases due to mineral or gas reactions

Barker and Torkelson (1975) have shown that newly broken surfaces will absorb fluid inclusion gases as they are released. Because H_2O is most strongly absorbed and it is the most abundant gas in the inclusions, this effect is not usually of first order importance in most aqueous inclusions (Norman and Sawkins 1987), although it can be important in inclusions of unusual composition or in extremely small samples (O.P. Landis, U.S. Geological Survey, Denver, Colorado, personal communication, April 1987). Changes in the composition of gases during and after their release from inclusions is probably a more important and less understood problem

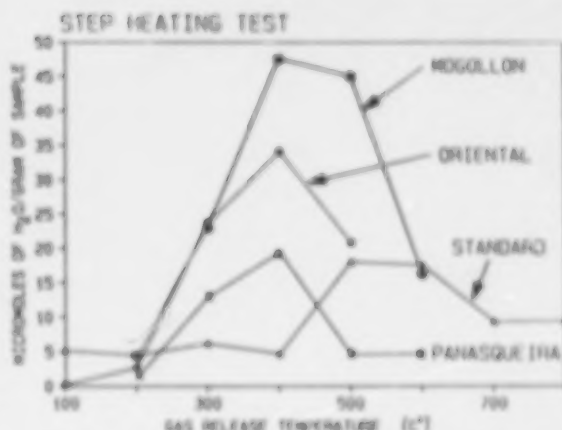


Figure 35.1. Results of step heating tests on fluid inclusions from the Mogollon epithermal Ag-Au vein deposit, the Oriental greenschist Au vein deposit, the Standard micron gold Au deposit, and the Panasqueira Sn-W vein deposit. H_2O yield, which is shown here as micromoles per gram of sample (inclusion-bearing material), increases to a maximum when most of the inclusions in the sample decrepitate and then decreases again. For Mogollon, Oriental, and Panasqueira, the H_2O maximum is 50 to 100 degrees above the homogenization temperature of most of the inclusions. The higher H_2O maximum for the Standard ore is related to the smaller size of fluid inclusions in the jasperoid host material and the consequent necessity to heat the sample considerably above the probable fluid inclusion homogenization temperature (Leroy 1979). Data shown in this diagram were obtained by P.S. Haynes and M.J. Gordenich using 1 g samples and gas chromatographic analyses.

(Mironova 1982). For instance, pyrolysis of organic matter, either in the inclusions or on the samples, can yield CO_2 , CO and CH_4 , as well as other alkanes and alkenes (Alexandrovska *et al.* 1980; Brower *et al.* 1987) and decomposition of carbonate at high temperatures ($>300^\circ\text{C}$) can release CO_2 . Reactions between gases during heating of the inclusions to decrepitation and/or between gases and mineral or analytical surfaces (such as steel tubing) can cause changes in the relative abundances of gas species (Norman and Sawkins 1987). The lack of "fluid inclusion standards" of known composition has hampered efforts to resolve some of these questions though this will probably be accomplished soon using synthetic fluid inclusions (Sterner and Bodnar 1984). Inclusion analyses can also be evaluated by determining whether the gases measured are in thermodynamic equilibrium at the temperature of homogenization and the $f\text{O}_2$ of the host mineral assemblage. For almost all published gas analyses, the carbon gases (CO_2 , CO, CH_4) yield unrealistically high equilibrium temperatures, apparently because the CO content of the gas assemblage is too high. In some cases, this can be attributed to post entrapment leakage of H_2 (Smith *et al.* 1984), although

this explanation is not likely for inclusions in younger, shallower rocks, suggesting that some anomalous CO values could be an artifact of the inclusion opening or analytical process.

As noted above, gases liberated from the fluid inclusions can be analyzed by either gas chromatography or mass spectrometry. Gas chromatography has relatively high detection limits that require inclusion-bearing samples no smaller than about 0.1 g in most cases (Cuney *et al.* 1976; Malakhov 1977; Smith *et al.* 1984; Kesler *et al.* 1986). Although some mass spectrometric methods also use bulk (1 g) samples (Norman and Sawkins 1987), detection limits of most systems permit the analysis of samples as small as individual fluid inclusions (Barker and Smith 1986). Whereas gas chromatography does not change the composition of the gases being analyzed, gas molecules are ionized and cracked during mass spectrometric analyses such that determination of the exact speciation of light hydrocarbons and the amount of H₂ in the original fluid can be difficult (Barker and Smith 1986; Norman and Sawkins 1987). Until fluid inclusion gas analytical methods are more widely standardized, the use of gas data for any purpose should involve careful assessment of all aspects of the analytical process for spurious results. In spite of these strong caveats, however, there seems to be light at the end of the tunnel, as indicated by the results summarized below.

EXAMPLES OF FLUID INCLUSION GAS SURVEYS FOR GOLD DEPOSITS

Adularia-Sericite Epithermal Vein Deposits

Fluid inclusion data on adularia-sericite-type epithermal vein deposits indicate that they formed from solutions with temperatures of 140° to 300°C

and salinities of less than 3 equivalent weight percent NaCl (Hayba *et al.* 1985). Isotopic data indicate that these waters were largely meteoric, with intermittent influxes of deeper waters (Kamilli and Ohmoto 1977; Casadevall and Ohmoto 1977; Bethke and Rye 1979; Vikre 1987). Depositional mechanisms in these deposits ranged from boiling (Kamilli and Ohmoto 1977) to cooling by mixing with groundwater (Hayba *et al.* 1985). Considerable interest has been focused on the boiling hypothesis because it involves loss of gases such as CO₂ and H₂S from the liquid that can, in turn, cause ore metal deposition (Drummond and Ohmoto 1985; Reed and Spycher 1985). Bodnar *et al.* (1985) have shown that the abundance of non-condensable gases such as CO₂ and H₂S will effect the depth at which boiling can occur, and Hedenquist and Henley (1985) and Drummond and Ohmoto (1985) have demonstrated that the relative abundances of H₂S, CO₂, and NaCl control the amounts of gold, silver, and base metals deposited by boiling.

Several studies suggest that gas haloes, possibly related to boiling, develop above ore shoots and therefore that surveys along barren veins exposed at the surface might provide evidence for buried ore shoots. Behr (1987) observed strong anomalies in total gas, N₂, and CO₂ (the dominant non-H₂O gases) over ore zones in the St. Cloud-U.S. Treasure vein (Figure 35.2). Behr *et al.* (1985) found gas abundances as low as 0.27 mole percent (of the ore fluid) at depth in this vein system, whereas values up to 2.45 mole percent were observed as much as 100 m above ore shoots. Gases detected in this and related surveys, which used thermal decrepitation and mass spectrometry, included CO₂, H₂S, H₂, CH₄, N₂, and C₂-C₆ hydrocarbons. Apocada *et al.* (1985) found that H₂S abundances in fluid inclusions from mineralized zones in veins at Cochiti,

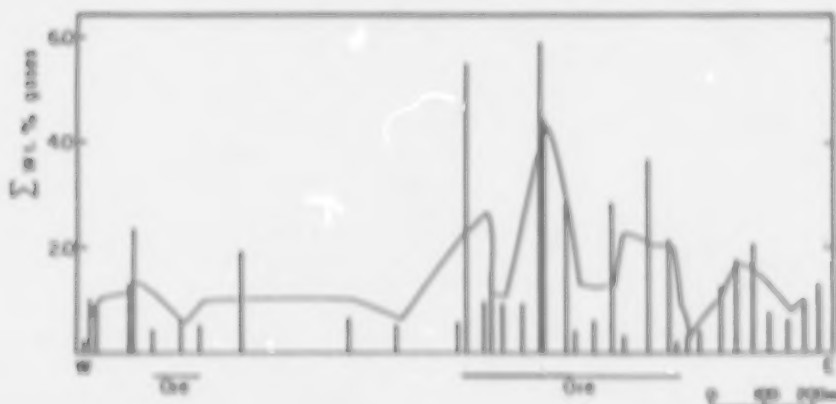


Figure 35.2. Total (non-H₂O) gas content of fluid inclusions (in weight percent) from samples taken at the surface along the St. Cloud-U.S. Treasure vein. Vertical lines are the analyses and the continuous line is a 3-point moving average. Ore zones are indicated by horizontal lines, with the major ore shoot represented by the heavy part of the line (from Behr (1987) with further explanation by D. E. Norman).

New Mexico were 0.25 to 2 mole percent, whereas inclusions in unmineralized veins contained only 0.002 to 0.003 mole percent H_2S . Oerdenich *et al.* (1986) reported that C_2H_4/C_2H_6 ratios in fluid inclusions above ore shoots were higher than in fluid inclusions above poorly mineralized vein sections at Mogollon, New Mexico. Kesler *et al.* (1986) have shown that gases desorbed from argillic alteration minerals overlying the inferred paleo-boiling zone at Creede, Colorado are highest in CO_2 over ore shoots.

Entrapment of fluid inclusions during boiling means that no pressure correction is required for the observed homogenization temperature (Roedder 1984). If an estimate of the fluid pressure can be made for boiling inclusions in a vein, then it is possible to reconstruct the hydrodynamic regime in the vein during mineralization. Loucks *et al.* (1985, in preparation) have pioneered the use of these geothermobarometry measurements to reconstruct fluid pressure gradients in epithermal vein systems. Loucks and Irish (in preparation) showed that accurate homogenization temperatures could be obtained from groups of 25 or more co-genetic boiling inclusions and Loucks and Sommer (1985) and Loucks *et al.* (in preparation) estimated pressures by measuring the abundances of H_2O , CO_2 , CH_4 , and H_2S in individual fluid inclusions. Fluid pressure gradients indicated by these gradients range from 8.7 to 9.1 bars/100 m for veins in the Topia, Mexico and Chloride, New Mexico districts (Loucks *et al.* 1985, in preparation) and the gradient indicated for the veins exceeds the hot-water hydrostatic gradient.

Loucks (personal communication, September, 1987) has summarized the potential application of these relations to exploration as follows:

"The explorationist can take advantage of this degree of thermal consistency among epithermal precious-metal-precipitating environments and the consistency of dynamic pressure gradients in boiling fluid columns by using fluid inclusion geothermobarometry on quartz samples from barren outcrop to estimate depth below the present erosion surface to a paleoisotherm (say, 250°C) deemed likely to lie in the fertile cleavage interval at which drill holes are to be targeted. For example, if the frequency histogram of homogenization temperatures of co-genetic inclusions that trapped boiling fluids in a sample of barren vein quartz yield an estimated mean trapping temperature of 160°C and chemical analysis of (gases in) inclusions that trapped the liquid phase show that it contained 0.2 molal CO_2 and and 0.3 molal (Na, K) Cl, then $PH_2O + PCO_2 = 35.0$ bars at 160°C and 46.4 bars at 250°C, if the liquid has neither lost nor gained CO_2 over this temperature interval. If the explorationist assumes a pressure gradient of 0.9 bars/m, based on accumulated experience, then the estimated depth from outcrop to the 250°C isotherm is $(46.4-35.0)/0.09 = 149$ m."

Although this method requires a relatively large number of sophisticated optical and chemical (gas) analyses, it appears to offer a method of estimating

directly the depth to ore in vein systems where only barren material is exposed.

It is by no means certain that most epithermal ores were deposited by boiling, however, and efforts have been made to devise gas surveys that would be useful in non-boiling settings. On the basis of gas analyses from 26 epithermal vein systems, Norman (1987) has shown that fluid inclusions from Au-Ag deposits "have H_2S concentrations >0.01 mole percent and generally higher levels of N_2 and organic compounds. Inclusions from Ag ores have H_2S concentrations of approximately 0.01 mole percent, whereas those from Au deposits generally have H_2S >0.1 mole percent." Norman has calculated that Au solubilities in these high- H_2S fluids would be 1 to 10 ppm, certainly high enough to form an ore deposit. Thus, even in the absence of boiling, the H_2S content of fluid inclusions might provide a means of distinguishing mineralized and barren systems. On a deposit scale, Norman (personal communication, October 4, 1987) has found that H_2S gas abundances correlate approximately with ore shoots at Cochiti, where boiling appears to have been important, although he feels that thermometric data are more useful than simple gas abundances in delineating actual ore shoots in most epithermal veins.

Acid-Sulphate Gold Deposits

Acid-sulphate gold deposits, which are considered a type of epithermal deposit by Hayba *et al.* (1985), consist of gold-rich precious metal mineralization associated with advanced argillic alteration containing pyrophyllite or kaolinite. These deposits probably formed at temperatures similar to those of the adularia-sericite deposits, although the mineralizing solutions were significantly more acid (Kesler *et al.* 1981; Stoffregen 1985). Chemical models for the genesis of these deposits involve the mixing of a magmatic vapour plume with groundwater and subsequent ore deposition when this solution is neutralized by reaction with wallrocks (Brimhall and Ghiorso 1983; Stoffregen 1985).

The only exploration-oriented fluid inclusion study of these systems involved analysis of inclusion gases from very fine grained silica, similar to jasperoid, that formed by replacement of volcanic rocks surrounding the Pueblo Viejo deposits in the Dominican Republic (Kesler *et al.* 1986). This survey, which used gas chromatography and thermal decrepitation from 1 g samples, showed a strong minimum in the CO_2 content of inclusion fluids over the area of most intense mineralization and CO_2 values of up to 6 mole percent in peripheral areas (Figure 35.3). A similar, but not as pronounced, decrease in CO_2 contents was observed with depth in the ore zone. The jasperoids analysed in this study were too fine grained to permit optical identification of fluid inclusions, although thin section study and sample treatment in acid eliminate the possibility that the high- CO_2 values are from decomposition of

to contain distinct CO₂-rich inclusions and comparison of the analyses with CO₂ abundances estimated optically for inclusions in the same samples indicated relatively good agreement (Smith *et al.* 1984). Thus, it is possible that these analyses reflect the presence of an upwelling plume of CO₂-rich fluid that was diluted by mixing along its periphery with wall-rock fluids. CO₂-rich gas analyses associated with mineralization have also been reported from possibly similar vein deposits associated with intrusive rocks in the Ukraine (Kaljushny *et al.* 1982).

Sediment-Hosted Micron Gold Deposits

Fluid inclusion research on sediment-hosted micron gold deposits has been hampered by the scarcity of ore-stage fluid inclusions that are large enough for study. Limited data obtained by Nash (1972); O'Neil and Bailey (1979); Radtke *et al.* (1980); Kuehn and Oize (1985); and Pasteris *et al.* (1986) suggest that the mineralizing fluid in these deposits had salinities less than about 1 molal NaCl, temperatures in the range of 250°C, and variable but locally high amounts of CO₂. Kuehn and Oize (1985) have suggested that CH₄(±CO₂) inclusions, which are also seen in these deposits, formed during pre-mineralization metamorphism of organic matter in the host rocks and are unrelated to the mineralizing process. Depositional mechanisms in these deposits are poorly known, but probably involved oxidation of the fluid, possibly by mixing with local groundwater (Radtke *et al.* 1980).

The composition of fluid inclusion gases in jasperoids surrounding several of these deposits was determined by Haynes and Kesler (1987) using gas chromatography. They analysed H₂O, CO₂, CO, CH₄, and N₂ in gases released from inclusions in 1 g samples by thermal decrepitation at 350°C. The 350°C decrepitation temperature was used because results of step-heating tests indicated that the maximum amount of C-gases were released between 250° and 350°C, suggesting that most of the fluid inclusions in the jasperoid had decrepitated by that temperature. The results of these analyses indicated that the average content of CO₂ and CO in jasperoids from mineralized systems is greater than that in those from barren systems. Within individual deposits, however, fluid inclusions from the central parts of the systems were lower in CO₂ and CO than those from the peripheral zones. The anomalous amounts of CO₂ and CO were interpreted to be from replacement of limestone during formation of jasperoid, which may have been more intense in mineralized systems. The lower values in the central parts of the mineralized zones could have been caused by more efficient flushing of these gases in the more highly permeable part of the deposit. Although the gas dispersion patterns observed in the micron gold deposits extended as much as 1 km from the central parts of the mineralized areas, none

had peak to background ratios greater than about two.

CONCLUSIONS

Available data on fluid inclusion gas compositions in hydrothermal gold deposits suggest the following preliminary conclusions.

1. Systematic variations in CO₂, CO, CH₄, and H₂S gas compositions throughout individual mineralized systems can be detected by analysis of gases released by thermal decrepitation of fluid inclusions in 1 g bulk samples. Although the dispersion patterns are relatively large-scale, most are not sufficiently strong to be first-order guides to exploration.
2. Analysis of individual fluid inclusions from boiling systems appears to permit determination of fluid pressure gradients in individual veins. These gradients can be used to predict depths to favourable temperature zones in buried vein systems in the same district.

Both techniques appear to offer most promise for the exploration of epithermal vein systems.

Use of these methods, however, requires considerable care in the selection of samples and analytical method, as well as in the interpretation of data, in order to avoid using analytical artifacts as exploration guides. Further studies are clearly needed to determine the most reliable methods for fluid inclusion gas analyses and the deposit types in which gas surveys would be most useful.

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36. Carbon Dioxide/Oxygen in the Exploration for Sulphide Mineralization

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ABSTRACT

CO₂ and SO₂ soil gas emanometry has been used to evaluate the subsurface potential for structurally controlled sulphides in 82 targets in northern Arizona. Sulphide mineralization, with up to 500 feet of cover, has been detected in controlled experiments. Repeated soil gas sampling was performed over a 12-month period for four targets. Toom to evaluate time of sampling, soil type, soil moisture, and depth of sampling indicate that soil moisture is probably the most important factor in CO₂ soil gas accumulation in this environment. A progressive decrease in the CO₂ soil gas signature is correlated to the decrease in the soil moisture content. The correlation between CO₂ and SO₂ is not a simple inverse relationship, but will frequently display an independent pattern.

INTRODUCTION

It is self-evident that the oxidation of sulphide minerals entails the consumption of oxygen. The initial source is molecular oxygen from the atmosphere, but this must pass into solution in groundwater or soil solutions before any reaction with sulphides is possible. Interstitial air in soils, overburden, or porous rocks forms an intermediate reservoir of oxygen between buried sulphides and the free atmosphere. The oxidation may be entirely chemical or may be enhanced by the microbial action of bacteria such as *Thiobacillus thiooxidans*. The oxidation of sulphides produces sulphuric acid which occasionally reacts with any available carbonates. The resulting carbon dioxide escapes into the subsurface surroundings and, ultimately, is lost into the atmosphere, into solution, or is consumed by autotrophic bacteria.

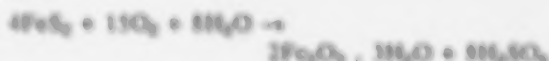
Thus the oxidation of a sulphide orebody leads to a consumption of molecular oxygen and, usually, production of gaseous carbon dioxide. Porous overburden forms a buffer in which restricted diffusion, dispersion, and replenishment mechanisms and retain anomalous gaseous activity. This paper presents data, collected repetitively over two areas of oxidizing sulphide, which indicates that the efficiency of this buffer varies seasonally and exerts a fundamen-

tal influence over the expression of the mineralization.

GEOCHEMICAL PRINCIPLES

It is rewarding and surprising to calculate the quantities of oxygen consumed by sulphides and the amount of carbon dioxide that may be generated.

If the oxidation of pyrite proceeds to limonite then:



then 1 t of pyrite will consume 1 t of oxygen and produce 1.6 t of sulphuric acid. If sufficient carbonate is available then the reaction:



will produce 0.72 t of carbon dioxide. The oxygen consumed has a volume of 700 m³ and the carbon dioxide generated will occupy 370 m³ at STP. With an atmospheric concentration of 20.9 percent oxygen, this would totally deplete 3350 m³ of air. If the gas is derived from within a rock or soil with a porosity of 20 percent, then the oxygen will be entirely removed from 16 750 m³ of cover. As diffusion and mass flow will tend to replace the lost oxygen, an overall fall of 1 percent O₂ could be produced in 150 000 m³ of overburden. The carbon dioxide produced would give a concentration of 0.33 percent in this same volume of rock or soil. It is unnecessary to point out that 1 t of sulphides would represent a very minor ore deposit.

The oxidation of sulphides may proceed with extreme rapidity, and spontaneous sulphide fires in mines have not been an uncommon occurrence. Bateman (1910), noted that a sulphide vein in a blind and warm mine at the Leonard Mine (Butte, Montana) was oxidized to a depth of 1 m within two years. At the Ely Mine, Nevada, a chalcocite ore in a bench in an open pit was oxidized so quickly that, at a depth of 10 to 15 m, about 15 percent copper within the ore was removed in solution.

Thus, there is a very clear potential for the development of anomalous gaseous concentrations within the overburden of a weathering sulphide deposit.

CARBON DIOXIDE AND OXYGEN IN MINERAL EXPLORATION

The possibility of anomalous levels of carbon dioxide and oxygen in soil gas being associated with oxidizing sulphide mineralization was first considered in the period 1954 to 1956 in the Soviet Union (Glebovskaya and Glebovskii 1960), and subsequent reports of this technique have been solely confined to the Eastern Bloc countries until quite recently (Lovell *et al.* 1979, 1980; Frick 1985; Hinkle and Dilbert 1984; McCarthy *et al.* 1986; Meyer *et al.* 1986).

There are numerous reports in the Soviet literature describing the use of CO_2/O_2 in soil gas as an exploration method (Kulikova 1960; Khayretdinov *et al.* 1965; Kravtsov and Fridman 1965; Glebovskaya 1969; Elinson *et al.* 1970; Dadashov *et al.* 1971; Fridman and Petrov 1976). In view of the volume of this literature and its apparent success in locating buried ore (Glebovskaya 1969), it is perhaps difficult to understand why this particular exploration tool has been largely ignored in the west.

CARBON DIOXIDE AND OXYGEN IN THE SUBSURFACE ENVIRONMENT

The extent to which oxidizing sulphides affect the composition of the subsurface atmosphere will, initially, depend upon the rate of oxidation and the intensity of other activities which remove oxygen and generate or remove carbon dioxide. The oxidation of pyrite was reviewed earlier in this paper and other sulphides of economic interest would be expected to behave in a similar manner. However, the stability of sulphides varies widely and the oxidation rates consequently differ.

The rate of oxidation of pyrite has been studied in the greatest detail, and may be summarized thus:

1. The oxidation of pyrite proceeds most rapidly below a pH of 3.5, at which point the activity of sulphide-oxidizing bacteria becomes the dominant cause. Above this pH, the oxidation is purely chemical.
2. Factors affecting the solubility of iron (high pH or high concentrations of phosphate ions) retard the oxidation of pyrite.
3. A high static water table restricts the circulation of atmospheric oxygen and will limit the sulphide oxidation to zones exposed to freshly oxygenated groundwater.
4. Low temperatures reduce the rate at which sulphides are oxidized.

It is probable that the conditions that most favour the oxidation of pyrite are those which are most likely to lead to a gaseous expression of this activity in the subsurface soils.

This paper demonstrates that the gases reach the surficial soils quite rapidly so oxidation should be proceeding as rapidly as possible at the time of sampling to yield a surficial expression. The following criteria are favourable for generating a diagnostic expression at the surface:

1. Sulphides should emerge above the water table at least during part of the year.
2. High ambient temperatures promote rapid oxidation.
3. A fluctuating water table increases the rate at which sulphides are oxidized. A falling water table may accentuate the expression.
4. The presence of the less stable sulphide minerals (pyrite, marcasite, chalcopyrite) is likely to lead to a better expression than a more stable sulphide mineral such as galena or sphalerite.
5. Low background microbial activity in the surface soil reduces the incidence of non-sulphide related anomalies.
6. Large concentrations of sulphides and distributions or fractures increase their exposure to oxygen.
7. A low pH and the absence of phosphate ions enhance the oxidation rate of pyrite.
8. The surficial soils must have a reasonable capacity to retain the anomalous gas concentrations.

Most of these criteria would be expected to be satisfied in the breccia pipe mineralization in the area around the Grand Canyon, Arizona, at least at appropriate times of the year.

However, the oxidation of sulphides is among the least important of phenomena that remove oxygen from the soil air and contribute carbon dioxide. The most important is the oxidation of organic carbon by microbial activity. It is important to achieve some understanding of these processes, so that soil gas data may be meaningfully interpreted.

It is interesting to consider the rate at which gas enters and leaves the soil air. Baver (1946) quoted several authors and estimated that there would have to be a complete renewal of soil air every hour to a depth of 20 cm in a loam soil in order to maintain its usual average composition and microbiological activity. In poorly consolidated and very dry desert soils, the rate of aeration would be expected to be considerably greater. If there is to be an adequate expression at the surface, mineralization must clearly contribute carbon dioxide to the soil air at a rate commensurate with such a rapid aeration.

CONTROLS OF AERATION WITHIN THE NEAR SURFACE ENVIRONMENT

It is a maxim that nature abhors a vacuum. In fact, the reverse is true and nature abhors a concentration. Excessive concentrations of any gas tend to disperse until the gas is in equilibrium with its environment. Gases may move in one of three ways:

1. Mass flow: movement in the gaseous phase in response to an absolute pressure gradient.
2. Diffusion: movement which is a result of a partial pressure (concentration) gradient of an individual component of a gas mixture and is a consequence of the thermal energy of the gaseous molecules or atoms.
3. In solution: movement which is analogous to mass flow but the gas is in solution in a liquid phase, itself in motion as a result of a pressure, density, or gravity gradient.

The history of a given gas during its dispersion into the surrounding environment may be the result of any or all of these mechanisms. The predominant method will be a function of both the nature of the gas and its environment.

RELATIVE IMPORTANCE OF TRANSPORT MECHANISMS

The contribution of various mechanisms of gaseous transport in soils to the distribution of gases will clearly vary with individual environments. However, Baver (1946) summarized the estimates of several authors of the contribution of various phenomena to soil aeration:

- Barometric pressure change - 1%
- Temperature variation - 0.12-0.21%
- Wind action - 0.1%
- Rainfall - 6.8%
- Diffusion - 90%

This list clearly cannot be universally applied and it is probable that, in soils with a thick porous section, pressure change is more important and in arid areas with very porous soils, wind action may become more significant. The effect of aqueous transport of gases below the aerated zone is not likely to be important in conventional soil air sampling except where oxygenated groundwater enhances the rate of oxidation of sulphide minerals.

ANALYTICAL METHODS

The Russian literature is unfortunately deficient in adequate descriptions of the analytical systems that were used. However, amongst the methods that have been mentioned, all too briefly, are interferometry (Khayretdinov *et al.* (1965), thermal conductivity (Glebovskaya 1969; Kulikova 1969), and gas chromatography (Dadashev *et al.* 1971).

A great deal of the research that has been carried out into the concentrations of carbon dioxide and oxygen has been for the purpose of agricultural research, and there is a large body of literature describing different sampling techniques (e.g. Yamaguchi *et al.* 1962; Tackett 1968; Bunting and Campbell 1975). There is a comparable series of pa-

pers describing analytical methods which have generally relied upon gas chromatography (Tackett 1968; Bailey and Beauchamp 1973; Smith 1977; Bunting and Campbell 1975; Blackmer and Bremner 1977).

The chief characteristic that distinguishes these two gases from the others that have been used in mineral exploration is that the levels and changes in concentrations encountered are in the percentage range. Radon, mercury, helium, hydrocarbons, sulphur gases, and organic gas levels are usually in the ppb or ppm range. The analysis is thus much simpler. It is possible to perform the analysis in the field by the use of portable instruments, but improved productivity and analytical control favours the return of the sample to a laboratory.

To return the samples to the laboratory, the soil gases are transferred from the soil gas sample probe to a sample container by means of a syringe. The sample container (Figure 36.1) consists of a 15 ml steel cylinder that is fitted with a silicone rubber septum and a threaded cap-nut containing a soft lead plug. The metal-to-metal seal formed by the lead plug and the neck of the gas cylinders is demonstrably helium tight. The gas samples then may be returned to the laboratory, which may be either in the field or elsewhere, for chromatographic analysis.

The gas chromatographic analysis determines oxygen, nitrogen, and carbon dioxide. The chromatographic analysis utilized by the authors relies upon a 1 m composite analytical column. An outer column of molecular sieve separates oxygen from nitrogen and a concentric inner column of porous polymer separates carbon dioxide from a composite oxygen/nitrogen peak. The carrier gas may be either hydrogen or helium and detection relies upon a micro-thermal conductivity detector. The data are collected on a chromatography data station which is programmed to achieve a precision of better than ± 0.05 percent for oxygen, nitrogen, and carbon dioxide. A typical chromatogram is shown in Figure 36.2.

Recently mass spectrometry has been suggested as a rapid alternative method of determination of gases at concentrations above about 0.1 percent v/v (Anderson *et al.* 1972; Nerken 1972; Ball *et al.* 1973; McFadden 1973; Newton *et al.* 1975; Robertson and Bracewell 1979; McCarthy *et al.* 1986). The chief advantage of mass spectrometry is that argon may be determined far more simply than by gas chromatography and many other species may be determined at trace levels (McCarthy *et al.* 1986).

Ball *et al.* (1983) and Gregory and Durrance (1985) have used a wet chemical analytical system. This apparatus relies upon measuring the volume changes which result from the successive chemical absorption of oxygen and carbon dioxide from the sample. However, the chemicals used are hazardous and the glass apparatus is not entirely suitable for

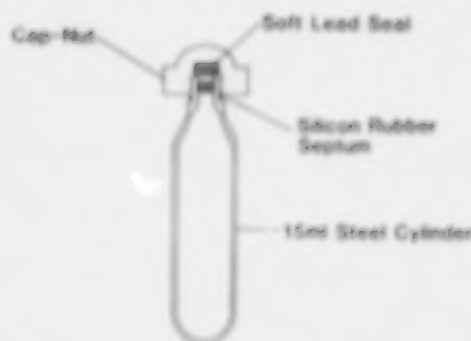


Figure 36.1. Cross-section of gas sampling cylinder.

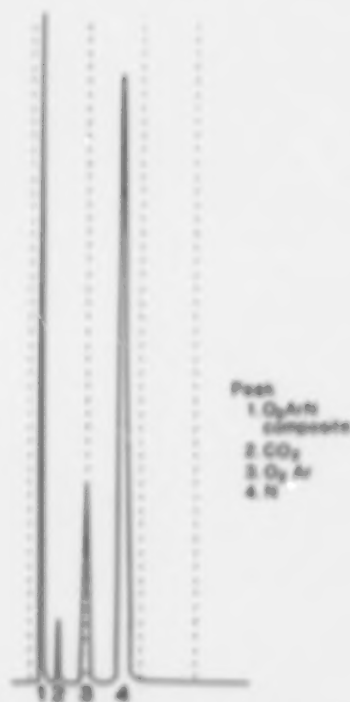


Figure 36.2. Chromatograph of soil air sample.

field conditions in remote environments. Governmental and airline restrictions on the transportation of hazardous chemicals would provide very severe constraints on the use of this approach. There is, however, one advantage, that of relatively low cost.

The use of absorbent and self-indicating analytical tubes may be possible and would provide an inexpensive method of determining the concentration of gases at the sample site. However, within the authors' experience, it has proved difficult to achieve acceptable levels of precision.

CASE HISTORY — THE COLORADO PLATEAU

The breccia pipe mineralization of the Colorado Plateau of northern Arizona (Figure 36.3) occurs in Palaeozoic sedimentary rocks. The mineralization, which may consist of massive concentrations of pyrite, uraninite, and sphalerite with associated lead, copper, and molybdenum sulphides, occurs in circular or oval pipe-like bodies with horizontal dimensions that are typically a few tens of metres, and vertical dimensions that may extend to 1000 m (Weinrich 1985). The pipes have been and continue to be important sources of copper, silver, and uranium. They appear to have developed over solution-collapse structures resulting from karstic weathering of Upper Mississippian to Triassic age in the Mississippian Redwall Limestone.

The surface expressions of the collapse structures include concentric, inward-dipping beds; circular areas of brecciated rock; circular bleached or ferruginous tonal anomalies; circular vegetation anomalies; and circular concave topography. However, not all of these structures are mineralized, and the concentrations of carbon dioxide in the overlying soils has proved to be a guide to the extent of the concealed mineralization, lying up to 500 m below the surface. The development of a gaseous expression of mineralization at such considerable depths beneath the surface is facilitated by a number of features, which include:

1. very high sulphide contents (10's of percent)
2. low water tables and continuous supplies of oxygenated ground water, as a result of the deep canyons that have developed in the area during the uplift of the Colorado Plateau
3. the isolated and transgressive nature of the breccia structures apparently favouring vertical gaseous movement and to limit the gaseous anomalies to the confines of the pipe
4. the low organic content and the poorly developed nature of the surface soils, leading to low background activity and permits subtle expressions of the mineralization to be recognized.

Figure 36.4 shows contoured soil gas carbon dioxide data collected from a maximum depth of 1 m, overlying a heavily mineralized breccia pipe. The maximum anomaly is only 0.3 percent CO_2 (just ten times the atmospheric background) but the circular gas anomaly is centred over the mineralization. The fact that data at these low concentrations are able to be contoured and then to accurately reflect mineralization at these depths (150–250 m) is a testament to the sensitivity and precision of the chromatographic analysis and to the low background soil activity.

This technique has been used routinely as an exploration tool in this area. However, prior to its adoption, a series of trials were carried out to determine the applicability and confidence levels of the



Figure 26.3. Index map of eastern Arizona showing the location of breccia pipes developed into mines.

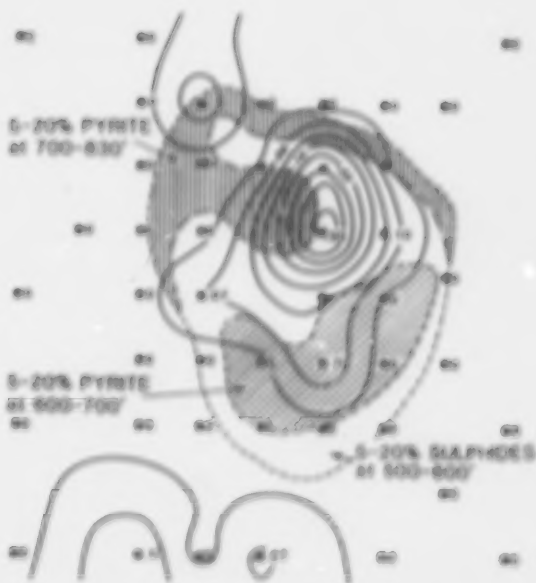


Figure 26.6. CO_2 content of tail air over mineralized breccia pipe, Arizona.

method in this area. From a series of 14 prospects, a total of 12 were subsequently drilled. By the use of the soil gas carbon dioxide data, it was possible to correctly predict both the presence and tenor of the underlying mineralization in 11 out of the 12 cases, an excellent success rate for any geological method.

However, the failure of the method in the twelfth case was a matter for some concern, since it failed to detect a very well-mineralized pulp. The

sampling was carried out during the late spring to early summer.

The failure in this one case notwithstanding, the method was applied to a series of exploration targets. It was a matter of some concern that none of the targets returned any detectable concentrations of carbon dioxide in the soil gases. Resampling of areas which had previously been shown to contain carbon dioxide related to mineralization in the overburden also failed to generate a response.

This sampling was carried out during the summer months and it was surmised that the very dry soils had no capacity to retain gaseous concentrations that were significantly out of equilibrium with the atmosphere.

Figure 36.5 shows the results of monitoring a single grid for a period of several weeks. As the soil dries, the anomalous portion of the grid, which corresponds to sulphides, fades and shifts. A later survey, after heavy overnight rain, showed that the anomaly became reestablished and demonstrates the continuous evolution of carbon dioxide from its source.

Surveys that were carried out after rain and snowfall during the winter months showed that anomalous concentrations were again detectable, including the previous failure of the twelfth case. Helium, radon, and oxygen concentrations did not serve to distinguish the mineralized pipes.

INTRODUCTION TO TIME STUDY

The need to determine the optimal time of the year to sample oxidizing sulphides for evolved CO₂ gas was realized early in the evaluation of CO₂ soil gas as an exploration tool in this area. As described above,

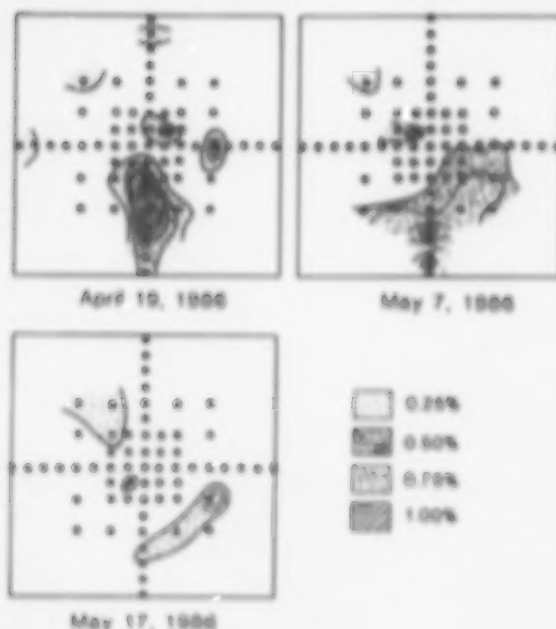


Figure 36.5. Disappearance of CO₂ from soil air in early summer over mineralized body.

In 1985 a known oxidizing sulphide body was compiled and it was found that samples taken in midsummer failed to detect the target, whereas samples taken in November, under 7 cm of snow, delineated the target perfectly. The following year (1986) it was decided to sample several targets as part of a production program for sulphide evaluation, at the same time continuing to refine the understanding of the effect of seasonal variation on target delineation.

GENERAL STUDY (82 TARGETS)

During a 46-day period in 1986, from mid-April to the end of May, an extensive sampling program collected 4805 samples over 82 selected areas. The time frame was kept as short as possible given that evidence existed from the small sampling program in 1985 that the "sampling window" would be sensitive to conditions of soil moisture and spring rains.

The areas sampled were randomly chosen, i.e. no prioritizing list was prepared. The order of sampling, as determined by the contract crew, was based upon closeness to the last sampled area, and the proximity to a mobile base camp. For this reason we believe that the following results are from random samples, and do not reflect a bias towards sampling high potential targets early in the program.

DATA DISCUSSION

SOIL MOISTURE

Figure 36.6 shows the decrease in soil moisture with time from mid-April to early June for four control areas which are representative of the total region. The decrease in soil moisture is significant since it parallels the decrease in measured rainfall at the same time.

PROBE DEPTH

At each sample site the depth of penetration of the sample collection probe was recorded. The comparison of the probe depth and the number of samples with CO₂ greater than the detection limit shows a slight positive correlation, but a Spearman Rank correlation gave a value of 0.0187, below the critical value of 0.0478 at a 95 percent confidence level and for $n=1187$.

CO₂ SAMPLES

The CO₂ soil gas data is shown in Figure 36.7 as samples where the CO₂ measured was above the detection limit, expressed as the percent of the total number of samples taken on that day. There is a strong decrease over time of the percent of CO₂ above the detection limit. This decrease parallels the decrease in soil moisture noted in Figure 36.6.

Figure 36.8 shows the mean of CO₂ values above the detection limit for each day's sampling. The data shows a random distribution with no change in trend for the mean values over time, supporting the contention that the data was collected randomly. These three graphs, taken in conjunction, demonstrate that samples collected earlier have a better statistical representative for data interpretation and a graphical presentation.

SUMMARY - GENERAL STUDY

The extensive data collected (4805 samples) in 46 days allowed an appreciation of the sensitivity of the

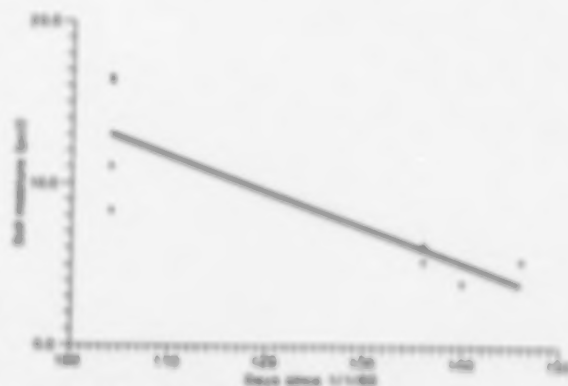


Figure 36.6. Soil moisture as weight percent measured by weight loss on drying.

SPECIFIC STUDY (4 CONTROLS)

INTRODUCTION

Four control areas were chosen for a continuing study of the relationship between CO_2 , soil moisture, rainfall, season, and depth of penetration of the sampling probe. The control areas were sampled on a monthly basis from May 1986 through December 1986. The controls A and B are 12 km (7 miles) apart. Controls C and D are 19 km (11.5 miles) apart. The distance between the two groups of controls is 119 km (71.5 miles). Controls C and B were treated as 'barren systems' since they do not have significant sulphides present. Controls A and D have abundant sulphides present.

DATA DISCUSSION

SOIL MOISTURE

At each sampling period for this time study, soil samples were taken for estimation of soil moisture by sample drying. Several samples were taken at each control area and the data averaged for that day and control area. The following graph (Figure 36.9) shows the plot for each of the four controls from April to December 1986.

RAINFALL

Rain gauges were set up at the four controls used for the time study. One rain gauge was vandalized during April by the addition of 6 cm of a cola drink to the rain gauge tube. That data has been excluded. The plot of the rainfall is the accumulated rainfall between sampling visits plotted for each control (Figure 36.10). A very strong correlation for rainfall is evident for each month's data between control areas. The correlation between soil moisture and rainfall is not always direct. The soil moisture for control A seems to lag behind the rainfall by two weeks. The

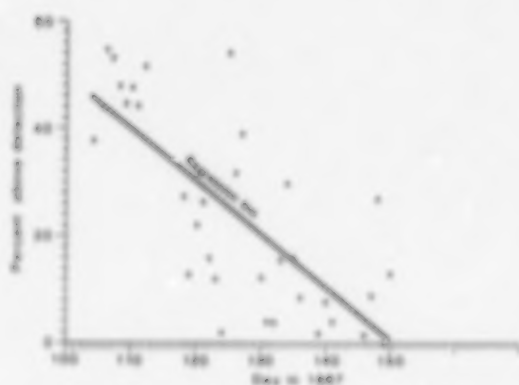


Figure 36.7. Percent CO_2 analyses above detection.

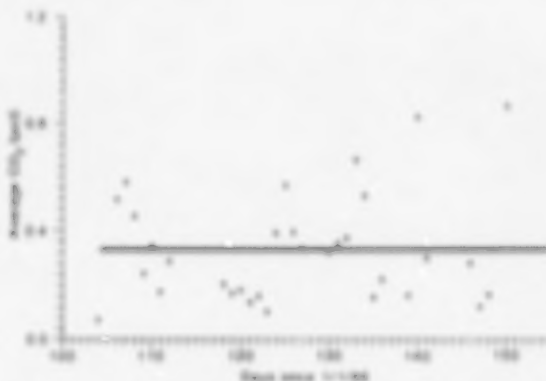


Figure 36.8. Average by day of CO_2 soil gas samples (mean includes only values above detection).

CO_2 soil gas method to a seasonal change for the manifestation of the CO_2 anomaly in a survey. The decrease in the number of samples above the detection limit for the method will change the level of statistical inference possible from the data. The relationship between soil moisture and the number of samples above detection is due, in part, to a capping effect of the moisture in the soil and the concomitant increase in accumulation of CO_2 below this cap. This capping effect has been noted in some earlier sampling over targets with frozen ground, or with a thin layer of snow cover. The increased moisture may also be involved in the generation of further CO_2 , but given the local environment in Arizona, there is probably some time delay.

Following this extensive sampling, the program continued by taking 60 soil gas samples over each of four controls once per month.

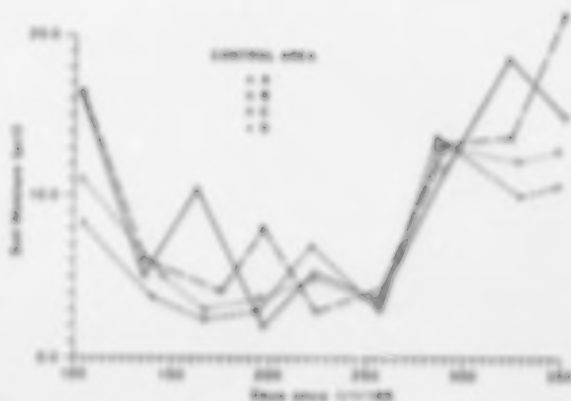


Figure 36.9. Soil moisture at weight percent measured by weight loss on drying.

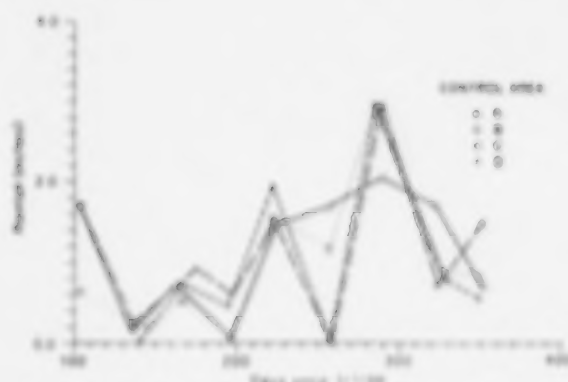


Figure 36.16. Rainfall totals by month.

other controls are representative of the correlation between soil moisture and the preceding month's rainfall.

CO₂ SAMPLES

Figure 36.11 shows one control (D) sampled over an eight-month period. This control has proven sulphides at a depth of 76 m (250 feet). The data show that the control is sensitive to the time of year for sample acquisition. During several months of the year (May, September, October, December) no CO₂ was detected, yet at other times the control area shows the location of an anomaly in the same general area.

The second control (Control A, Figure 36.12) also has sulphides at 76 m (250 feet). It shows a similar trend to Control D in that at a certain time (November, December) the control area has no discernible CO₂. When detectable CO₂ ions are present the overall contour pattern is similar between each sampling period for the target. Although a fall in the oxygen concentrations of the soil air over oxidizing sulphides has been reported, the oxygen content of these soil gases does not show any discernible pattern that reflects the presence of mineralization (Figures 36.13 and 36.14). This probably reflects the considerable depth to the mineralization with the result that the oxygen is principally derived from active groundwaters rather than the immediately overlying soil.

CONCLUSIONS

The long-term study of four control areas with known sulphide content has extended the general

study from 46 days to eight months. The results substantiate the more general data, that the development of a CO₂ anomaly is strongly dependent upon a CO₂ gas accumulating mechanism for a target. This accumulating mechanism may be: soil moisture, caliche, snow, or frozen ground. Any gas-accumulating mechanism must not, in turn, be a gas-excluding mechanism. Late in the study, the rainfall increased to above two inches per month and the soil moisture was measured at 12 to 20 weight percent. It would appear that this saturation of the soil by an influx of water has excluded or dissolved CO₂ gas from the pore spaces. It is particularly evident at Butte NE where the previous months' sampling had several stations with detectable CO₂, yet November and December are completely devoid of samples with detectable CO₂. Solution of the carbon dioxide would be favoured by the neutral or alkaline nature of the soils and the influx of a large quantity of fresh water. The anomalous CO₂ concentrations would be expected to reappear once the soil solutions are saturated.

The depth of penetration for the sampling probe does not appear to be too significant, at least when penetration is greater than 10 to 15 cm. Although some minor correlation can be noted between depth of sample acquisition and the mean CO₂ result, the Spearman Rank correlation statistic lacks significance at the 95 percent confidence level.

There is, however, a substantial body of evidence to support the belief that the concentrations of carbon dioxide and oxygen in soil gas can reveal the position of concealed mineralization even through considerable thicknesses of overburden.

The equipment required for surveys of this type is inexpensive and readily available. Numerous analytical techniques are possible.

There is also a very wide range of soil gas concentrations to be found in different environments and these may markedly vary with the seasons. It is extremely important when applying this technique to a given area to carry out local orientation tests to establish the true background and the contrast that may be expected. The continued monitoring of a control site is important to ensure that an adequate expression of the mineralization is being retained.

Future developments of this method may include the determination of stable isotope C₁₃/C₁₂ ratios. These would serve to distinguish between anomalous concentrations of carbon dioxide that have been derived from local variations in the soil microbial activity, and those that are due to the chemical destruction of carbonates or hydrocarbons.

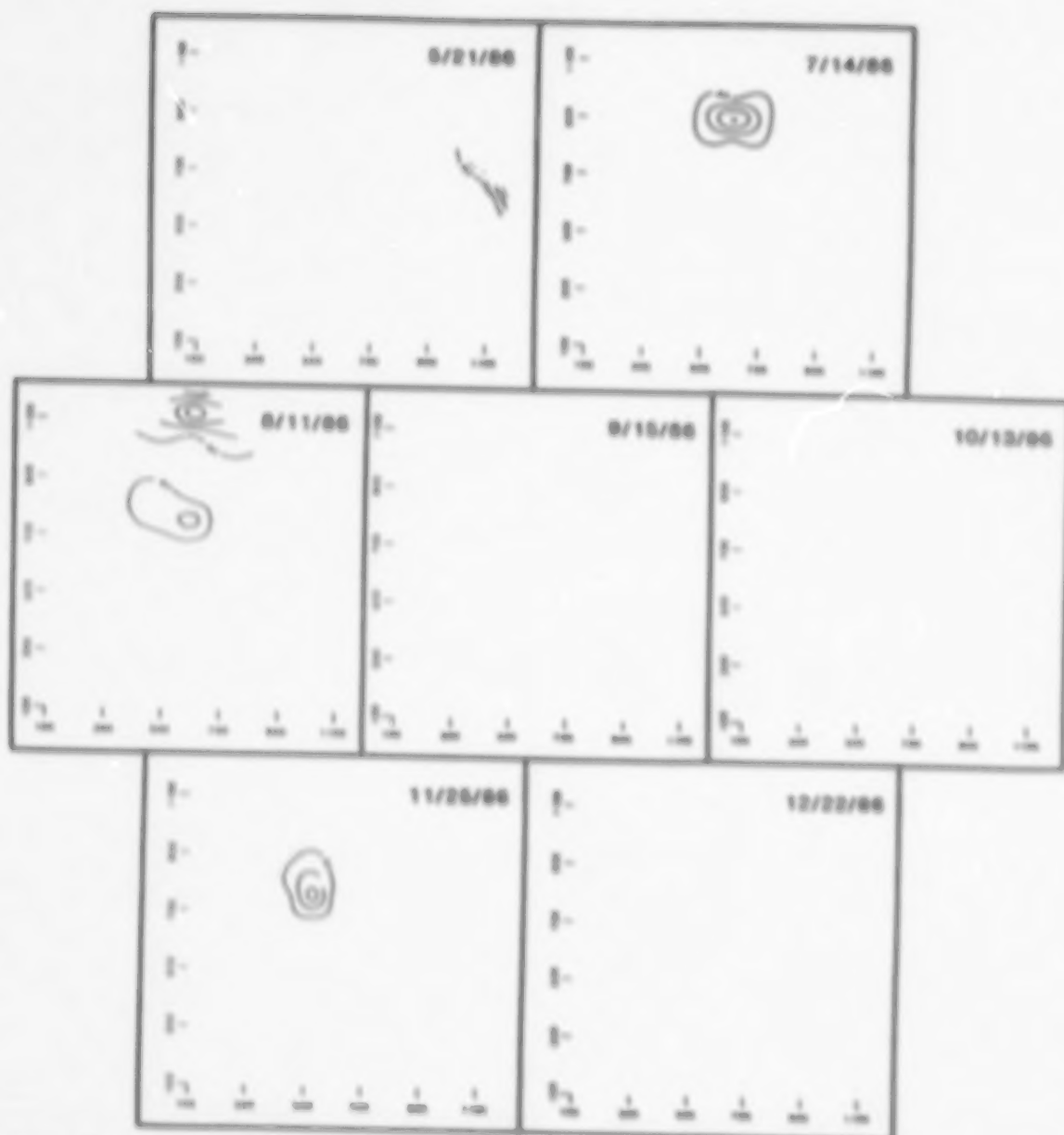


Figure 30.11. Carbon dioxide concentration of soil gases, Central Area "D".

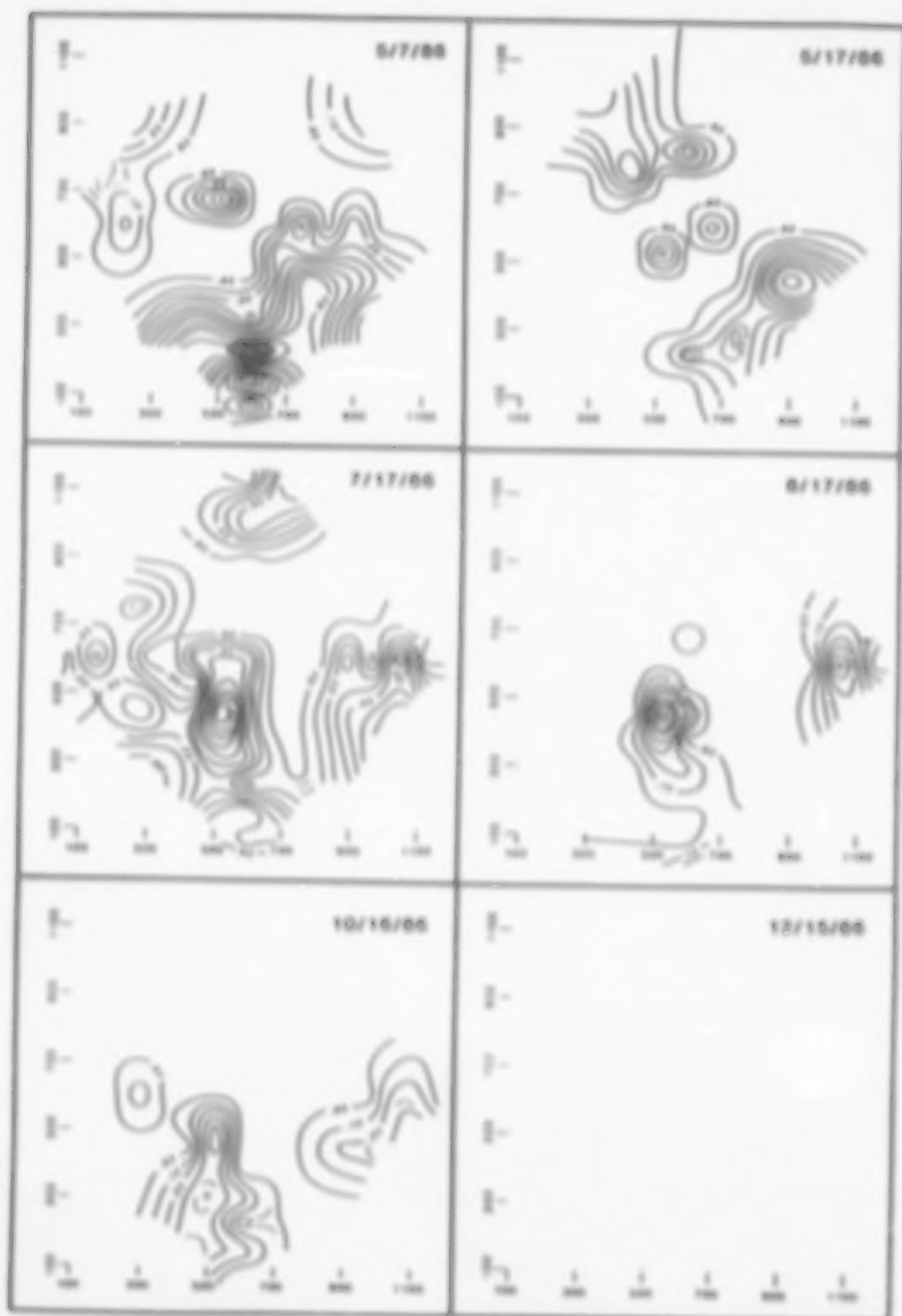


Figure 76.12. Carbon dioxide concentration of soil gases, Central Area "A".

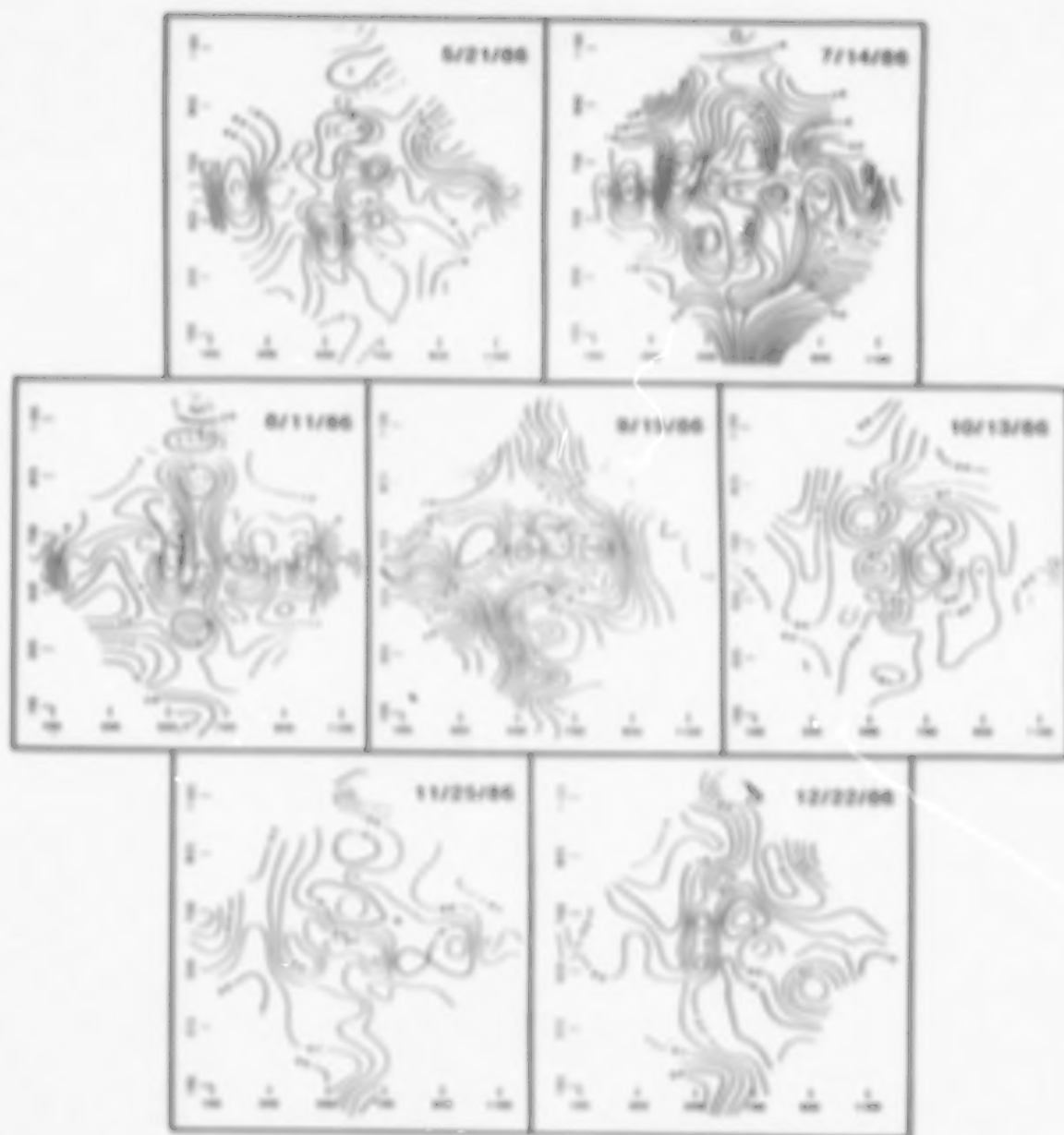


Figure 26.13. Oxygen content of soil gases, Control Area "B".

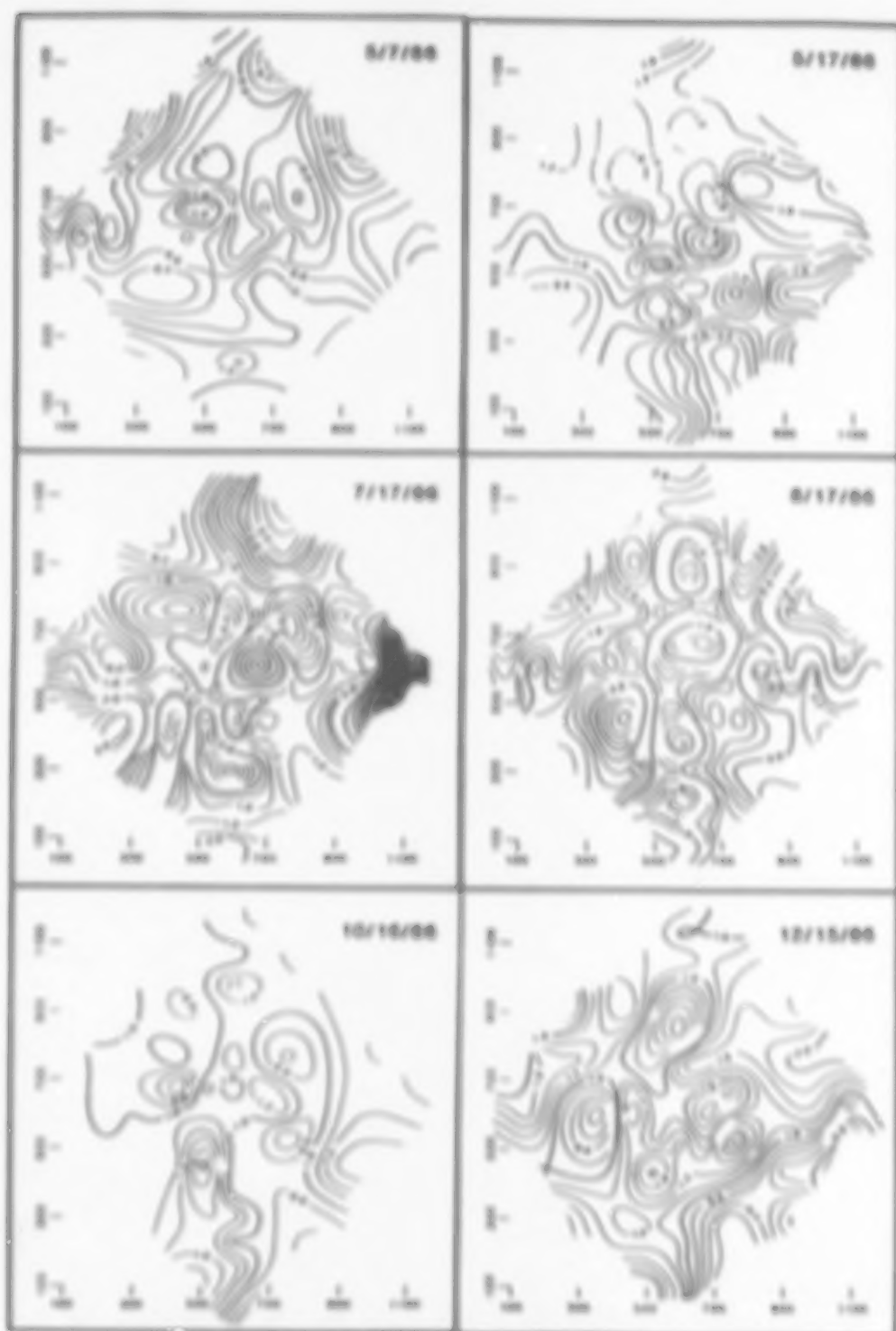


Figure 25.14. Oxygen content of soil gas, Control Area "A".

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Geophysical Methods: Their Application to Ore Exploration



37. Geophysics in Gold Exploration—Some Examples

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ABSTRACT

Gold, as it occurs naturally, is not directly detectable by geophysical methods. Its occurrence in a fairly specific range of mineral association and geological setting, however, permits its detection and discovery through identification of these minerals, and associated mapping of the geology by geophysics. Geophysical surveys are used to map large-scale geological features to explore for gold in covered terrains. Structure, an important element in many gold deposits, can be mapped by the use of airborne magnetic and electromagnetic surveys. Gold deposits in the Abitibi region of the Canadian Shield have a clear identity with structural features interpreted on the regional geophysical maps.

Magnetite is an important mineral in gold deposits. It may be present, as in the iron formation related to gold deposits at Pickle Lake, Ontario, or it may be absent, through destruction by hydrothermal alteration, as at Rotorua, New Zealand, where gold is being deposited at the present time. Magnetic surveys provide good definition of both settings.

Iron sulphides are the most common mineral associated with gold deposits. The amount of sulphides (usually pyrite) may vary considerably. Gold may occur on its own, or as an accessory mineral in base-metal polymetallic sulphide deposits. The sulphides may be detectable by electrical-potential or electromagnetic methods, as at the Chetwynd, Newfoundland, gold deposit and at the Selbaie, Québec, copper-gold-silver deposit. Silica, as well as sulphides, representing hydrothermal alteration in many gold deposits, may be a factor in the geophysical response. Some hope in recognizing different phases of mineralization, particularly that carrying gold, is offered by spectral induced polarization. A definitive answer was not achieved in the Chetwynd data.

The stratigraphy of deeply buried gold-bearing beds, may be resolved by seismic reflection surveys, as in the Witwatersrand Basin in South Africa. Seismic surveys in this region represent a significant new direction in exploration for gold.

INTRODUCTION

The opportunities for the use of geophysical methods in exploring for gold are as many and as varied as the geophysical mapping of rocks can provide. No narrowly defined method provides a unique signature for gold; all of the techniques employed for geo-

physical mapping may be used. Applications will depend on the target lithologies and their measurable physical characteristics. It is not the purpose of this paper to provide a comprehensive review of these geophysical methods and applications, but rather to highlight a few examples.

Gold deposits may be primary (syngenetic) or, more often, secondary (epigenetic) in origin, and they may have been formed at any time from the Archean to the present. They show common as well as significantly divergent physical and mineralogical features, which are useful for the application of geophysical methods. Geophysical survey results can provide both direct and indirect guides to finding gold ore. More often, the indications are indirect, as geophysical methods map minerals and structures in the associated rocks. Some gold deposits do not lend themselves to detection by geophysical methods.

GENERAL

Geophysical techniques have been widely and successfully used to explore for gold for more than 50 years. A review of the literature shows there is a very broad base of published material. Two recent symposia on geophysical exploration for gold were held in Canada (CIM 1984) and Australia (Doyle 1984). Doyle (1986) has presented a review of applications. Other references are presented here. Historically, the most successful contribution by geophysics, in terms of the amount of gold eventually discovered, was made in the Witwatersrand Basin in South Africa, where in the 1930s, magnetic and gravity surveys provided an early base of information (Roux 1967). Recently, the new application of deep reflection seismic surveys has continued the tradition of geophysical mapping of ore-bearing structures in the Witwatersrand (Campbell and Peace 1984). The direct search for gold-bearing structures has not been common. From the mid-1950s to this decade, gold has been discovered, through the use of geophysical surveys, as a by-product of the search for base-metal sulphides. Much of this exploration has focused on the use of electromagnetic and magnetic methods. At the present time, geophysical methods are being used at both regional and detail scales to describe the geological/geophysical setting of deposits which may be either gold only deposits or deposits containing by-product gold.

The concentration of gold in rocks is always too low to be detected directly by geophysical methods, so indirect methods must be employed. An understanding of the geology and mineralogy of gold de-

posits is essential for the successful application of geophysical methods. While the scope of this paper allows only a superficial outline of geology and mineralogy, some characteristics need mention. There is, for instance, a common association of gold with sulphides. Most often this is pyrite, as in the Hollinger Mine, Ontario (Spooner *et al.* 1985). After pyrite, arsenopyrite may be the dominant sulphide; pyrrhotite and chalcopyrite may be present as well. The percentage of sulphides may vary widely. At Agnico, Québec, sulphides may constitute 70 percent of the ore (Barnett *et al.* 1982). At Hemlo, Ontario, sulphide content averages 8 percent (Harris 1986), while some deposits such as the Powell Rouyn Mine, Québec, show a low average sulphide content (3 percent), but increasing gold with increasing sulphides (McMurchy 1948). There can be an association with magnetite, although sulphides in crosscutting structures generally carry the gold. For example, with pyrrhotite in the Central Patricia Mine, Ontario (Barrett and Johnson 1948), and with pyrite in the Golden Mile, Western Australia (Clark *et al.* 1986).

Irrespective of rock type, there is often a relationship between gold deposits and the structure of the rocks in which they occur (Roberts 1987). Large through-going crustal breaks have a significant impact on the localization of gold ore (Andrews *et al.* 1986). These may be seen as distinct breaks in lithology, as with the Porcupine-Destor Fault; or as lines of weakness along graphitic horizons, as in the Casa-Berardi area. Both of these features are in the Abitibi region in Canada. Quartz veins and/or silicification are common features of the structurally related gold deposits, while pyrite or other sulphides may be only a minor constituent, as in the Sigma Mine in Québec (Robert and Brown 1986).

Gold can occur in alluvial (placer) or paleoalluvial environments. Uranium, as well as pyrite, may be an associated mineral in paleoalluvial settings, as in the case of the Witwatersrand deposits (Hallbauer 1986). A good review of the Witwatersrand, as well as of placer deposits, is provided by Boyle (1979).

Considering the physical attributes that these geological and mineralogical conditions impart, it is possible to recognize a number of geophysically detectable signatures, which may be used directly or indirectly to map the environments of gold deposits. All of the presently employed families of geophysical methods can be used in the search for gold. Examples of the use of magnetic, electromagnetic, electrical-potential, and seismic methods are presented here.

MAGNETIC SURVEYS

THE ABITIBI REGION, ONTARIO AND QUÉBEC, CANADA

The Abitibi region of northern Ontario and Québec is the major gold-producing area of Canada. Vol-

canic and sedimentary rocks of Archean age (2700 Ma) are the host. Glacial erosion, as recent as 10 000 years ago, has produced a subdued terrain with a fresh, unweathered bedrock surface. These rocks may be exposed on surface or covered with up to a few tens of metres of glacial debris, which may be combinations of gravel, sand, or clay. This physiographic and geological aspect encourages the extensive use of airborne and ground geophysical methods, which can map various physical characteristics of unweathered rocks under covered terrain.

Contours of the total magnetic field collected by an airborne magnetometer survey in the Rouyn-Noranda part of the Abitibi region are shown in Figure 37.1 (GSC 1948). Sensor height above local terrain was 305 m (1000 feet), with a flight line separation of 805 m (0.5 miles). This was sufficient to resolve medium- to large-scale features. The map was originally published at a scale of 1:250 000.

Thick lines have been drawn on the map to show the locations of the Porcupine-Destor Fault (P-D) to the north, and the Kirkland-Larder Lake and Cadillac Faults (K-LL and C) to the south. Some major subsidiary faults are also shown. Open circles of three different sizes identify gold only deposits: up to 10 000 ounces, 10 000 to 100 000 ounces, and over 100 000 ounces contained gold (MERQ 1981; Hodgson 1983). These numbers represent both production and reserves. The Kerr-Addison Mine on the Kirkland-Larder Lake Break produced nearly 10 million ounces of gold. The Horne Mine at Noranda was primarily a base-metal mine, however, its production of over 10 million ounces of gold represents the largest single gold producer in the Noranda area. Gold production from other gold mines in the Noranda area was 3.55 million ounces up to 1979 (Franklin and Thorpe 1982).

Geological maps of the area identify various sequences of volcanic and sedimentary rocks (MERQ-OGS 1983). The rocks that have developed in the vicinity of the faults are strongly magnetized, while the rocks lying away from the major structure generally have lower magnetizations. As a result, the faults are often sharply defined by long linear highs and lows, as well as by pattern interruptions.

The importance of the major structures in the emplacement of gold in the Abitibi region is demonstrated by the way the gold deposits cluster along their length. In places, deposits are on the main faults, but more often they are located on subsidiary structures. This is indicated by the scatter of occurrences. These structures are the most important gold-bearing features in the Abitibi as a whole. Production from all sources has been about 130 million ounces. Eighty percent of this has come from gold only producers lying on or close to the major breaks. Not shown are the other major gold production centres at Timmins, on the Porcupine-Destor Break; Kirkland Lake, on the Kirkland-Larder

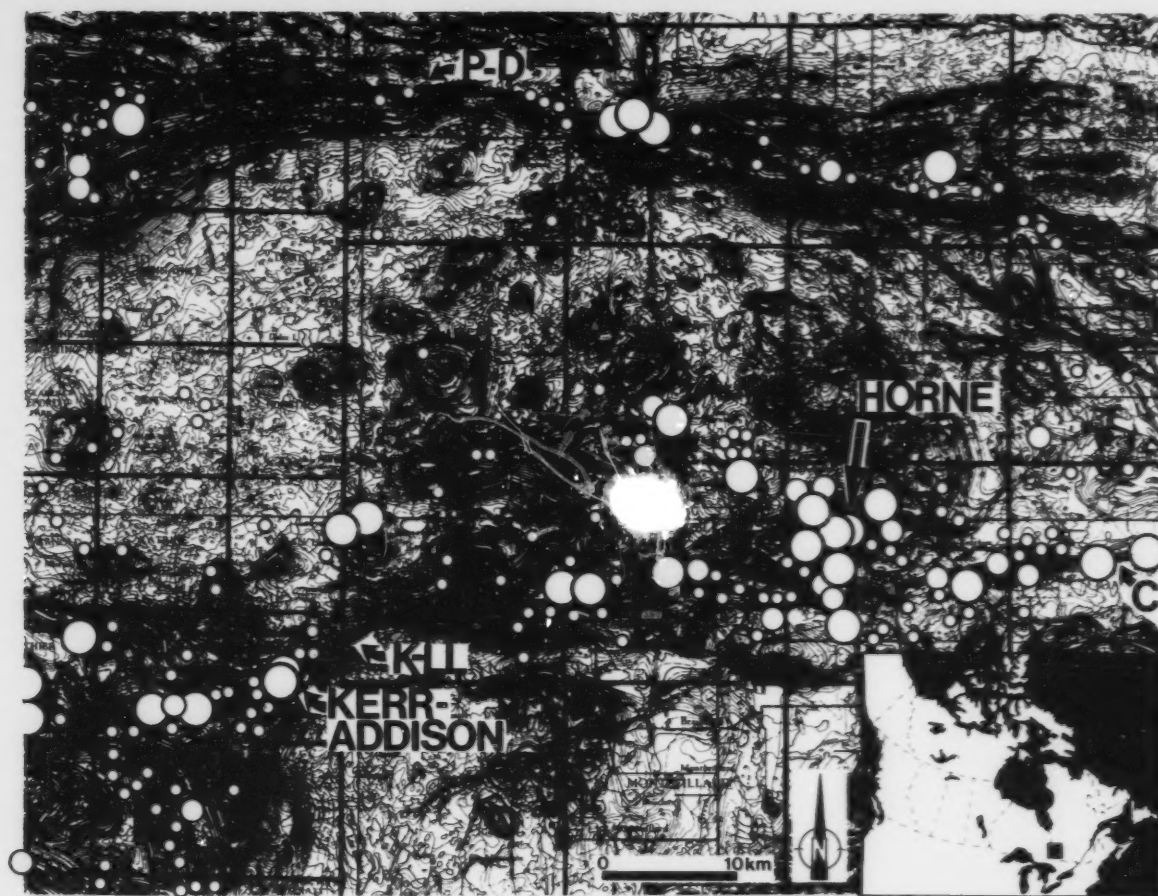


Figure 37.1. Airborne Magnetic map of the Rouyn-Noranda area, Ontario and Québec, with major structures and gold deposits (GSC 1948). The contour interval is 10 nanoteslas (nT).

Lake Break, both to the west of Figure 37.1; and Val d'Or on the Cadillac Break, to the east of Figure 37.1.

The magnetic map shows closed magnetic highs in the region between the major breaks. These identify intrusions of both acidic and mafic composition. These appear in places, to have some influence on the emplacement of gold. This situation occurs in the vicinity of the Horne Mine, although it is not well seen on Figure 37.1, as the circles used for deposit indicators obscure the contours which identify the active magnetics at this location.

New gold deposits continue to be found in the Abitibi Region. The Holt-McDermott Mine, on a splay fault southwest off the Porcupine-Destor Fault, (upper left on Figure 37.1) contains over one half million ounces (Workman 1986). Five kilometres west of the Horne Mine, the Silidor Deposit contains nearly one million ounces of gold in a north-northwesterly cross break between major subsidiary faults (Francoeur 1987). While neither of

these discoveries was assisted greatly by geophysical surveys, because of the lack of geophysically identifiable mineralization, these and other new deposits of the region are well identified with structures subsidiary to the main breaks observed on the magnetic contour maps.

There would appear to be a continuing role for the magnetic survey data in the Abitibi as exploration continues, by helping to identify structures which may contain gold. The synoptic assembly of information in Figure 37.1 can also provide a useful guide to exploration in other less well-developed areas.

PICKLE LAKE, ONTARIO, CANADA

The gold deposits of the Pickle Lake region are shown in Figure 37.2. These are identified directly with magnetic highs caused by magnetite iron formation. This is in direct contrast with the Abitibi region, where gold deposits are not specifically identified with magnetic highs.

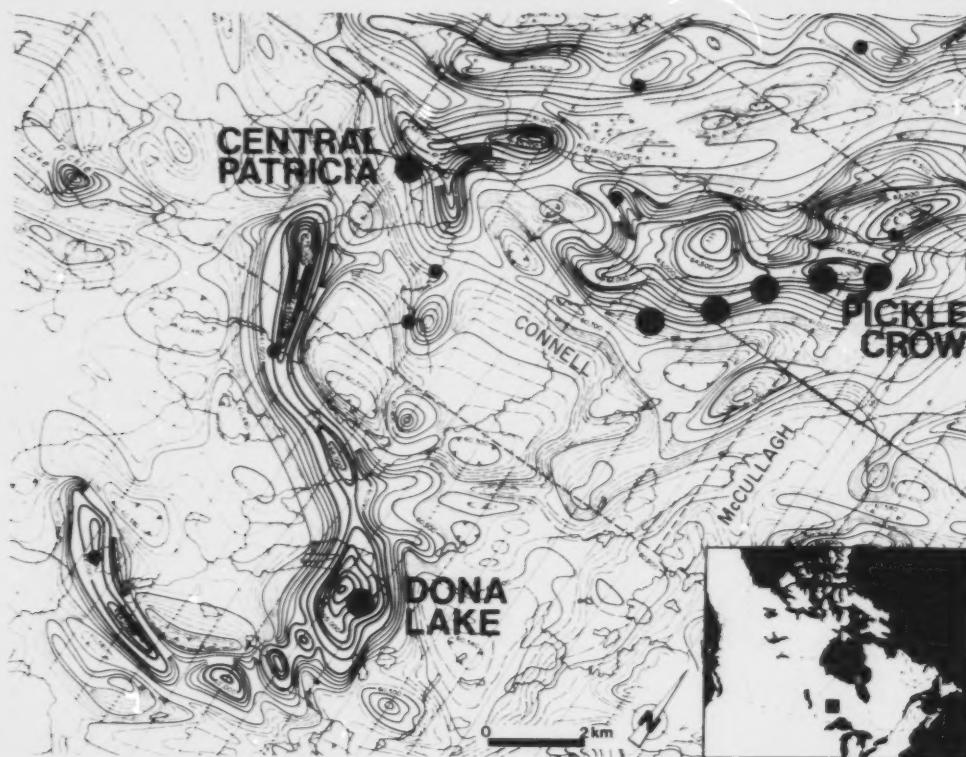


Figure 37.2. Airborne Magnetic map of the Pickle Lake area, Ontario, with gold deposits (GSC 1959, 1960). The contour interval is 20 nT.

Figure 37.2 is taken from data originally published at a scale of 1:63 360 (GSC 1959, 1960). Archean rocks of the area have an age of 2700 Ma. Mines at Pickle Crow and Central Patricia have produced 2.1 million ounces of gold, while the new discovery at Dona Lake has identified a further half million ounces of gold.

It is quite evident from the distribution of the gold deposits in Figure 37.2 that there is a close association between the deposits and the magnetic highs which define the iron formation. The coincidence may not be direct as deposits appear in places to flank the strongest magnetic horizons. As well, there is a suggestion that the gold deposits associate with local structures, identified by breaks or folds defined by the magnetic contours. The geology of these deposits, outlined by Barrett and Johnson (1948) and Corking (1948), supports these observations, showing both the direct correlation of ore with the magnetite iron formation, and the local control by crosscutting structures.

ROTORUA, NEW ZEALAND

A very different magnetic expression of gold deposition is shown in Figure 37.3. Magnetic data are from a helicopter-borne magnetometer survey flown in

the Rotorua area of New Zealand for BP New Zealand (R.G. Adamson and C.B. Moore, BP Oil New Zealand Limited, Minerals Division, Wellington, New Zealand, personal communication,

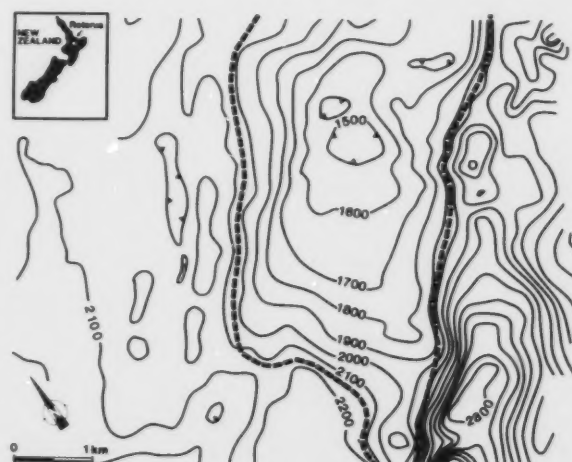


Figure 37.3. Airborne Magnetic map from the Rotorua area, New Zealand. The contour interval is 100 nT. The dashed lines suggest the boundaries of the thermal system.

1986). The striking feature on this map is the broad magnetic low which is fairly sharply bounded and shows linear extensions south and west. This magnetic low lies over a recently active geothermal system. It is evident that magnetite in the country rock has been destroyed by the thermal activity.

Gold is known to be depositing at the present time in the thermal systems in Rotorua. Weissberg (1969) reported up to 85 ppm of gold along with 500 ppm of silver in hot pools in the region. Interestingly, pyrite is a common accessory mineral.

The magnetic mapping of this and other dormant thermal systems can make a significant contribution to the search for gold deposits by mapping the extent and detailed character of the thermal system. The various linear features seen in the magnetic map are of importance in this search as they may mark sites of gold emplacement, or conduits for the thermal fluids carrying the gold.

ELECTROMAGNETIC SURVEYS

BOUSQUET-CADILLAC AREA, QUÉBEC, CANADA

Electromagnetic surveys are used to map conductive minerals which have distributions often associated with gold deposits. Such conductive minerals are sulphides and/or graphite, which may be identified in both airborne and ground electromagnetic surveys.

Input airborne electromagnetic surveys have mapped large areas of the Abitibi region of Québec. Figure 37.4 presents a map of Input responses over a portion of the Cadillac Break just east of the area shown in Figure 37.1 (MERQ 1971). The number of channels of response of the system is represented by progressively closed circles. A two channel response is an open circle, a six channel response is a fully closed circle. Correlation with a magnetic response is indicated by a second enclosing circle. The original scale of the map was 1:31 680 (1 inch to 1/2 mile). The survey was flown with an aircraft height of 150 m with a line spacing of about 200 m. A number of gold mines are presently operating in the region, including the Doyon, Bousquet, and Dumagami Mines. Other deposits and mines are identified. Some of these lie on the main break, while the large producers lie on or near an adjacent linear feature to the north.

Electromagnetic responses define a number of linear events which, in places, directly correlate with mines and deposits. The source of these responses is primarily pyrite, possibly marking bedded sequences within the volcanic and sedimentary terrain. The conductor and the geological base map presented, imply a primary or syngenetic origin for the pyrite, and its associated gold. A secondary hydrothermal origin for both sulphides and gold within structures associated with the Cadillac Break, is a likely alternative interpretation.

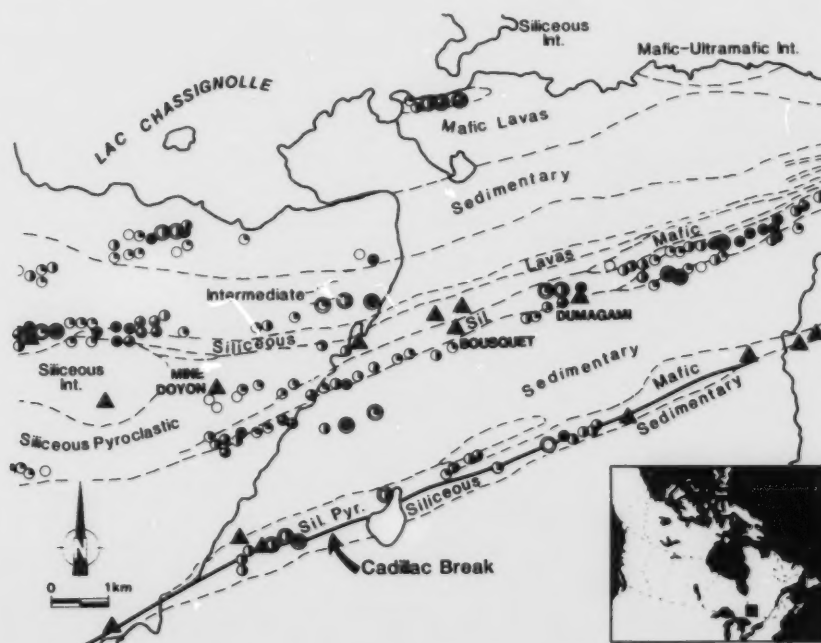


Figure 37.4. Airborne Input EM electromagnetic responses (open and closed circles) in the Bousquet-Cadillac area, Québec. Geology and gold deposits (solid triangles) are identified (MERQ 1971).

Some deposits such as Dumagami appear to be directly associated with the conductive pyrite. Other deposits while variously related to pyrite such as Mine Doyon (Savoie *et al.* 1986), are not directly identified by the electromagnetic survey. It is evident that the electromagnetic survey has mapped a number of conductive mineralized events useful in the search for gold, but these cannot be used as an exclusive identifier of the gold deposits.

LES MINES SELBAIE, QUÉBEC, CANADA

Farther north in the Abitibi region is found Les Mines Selbaie, which is producing copper-gold-silver from its B zone (Deptuck *et al.* 1982). An Input airborne electromagnetic survey was employed to discover the deposit (Reed 1981). Figure 37.5 is a map showing the Input EM anomalies, combined with contours of the induced polarization, frequency effect response, over the A and B zones. The A zone is a zinc-copper-silver-gold deposit in which gold makes only a small economic contribution. Gold in the B zone, however, has contributed between 20 percent and 25 percent of the economic return.

The B zone is a fault remobilized pyrite and chalcopyrite sulphide body. It contains 1.3 grams of gold per tonne, along with 3.5 percent copper, and 35 grams per tonne of silver. The value of the gold produced represents the difference between profit

and loss. The B zone, then, is not an economic orebody without the contribution from its gold.

Input EM and induced polarization surveys played a primary role in finding and defining the deposit. Together these mapped the extensive area of sulphides shown by anomalous responses in Figure 37.5. More recent exploration efforts have concentrated on borehole electromagnetic surveying (Reed 1986), to identify more deeply buried sulphide lenses. These may lie near drillholes, but not be intersected by the holes. Figure 37.6 shows the plot of three drillholes, and the electromagnetic response in one of them. The response identifies a previously unsuspected lens of some 150 000 tonnes of ore, which was subsequently drilled as a consequence of these survey results. The survey instrument was a Crone PEM system (Crone 1986), using a receiver lowered into holes drilled from underground. The transmitter was on surface over the area being surveyed. The PEM system used synchronized clocks so that no physical link was required between the surface transmitter and the underground receiver. The large response at about 75 m in the hole suggested an off-hole source at the location shown in Figure 37.6. The other holes shown obtained similar results. A borehole drilled from the 240 m level in the mine, intersected the target body. While small in

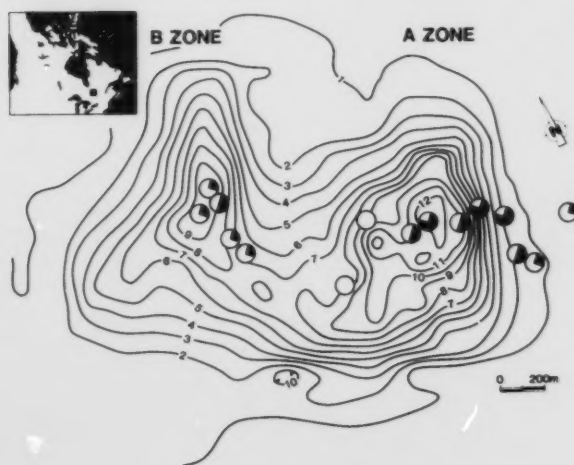


Figure 37.5. Combined Mark VI Input EM and induced polarization responses over Les Mines Selbaie, Québec. Input EM anomalies are identified by open circles (channel 2) and partly closed circles. Each additional channel is represented by a one quarter closure. IP responses are contoured at intervals of 1 PFE. Data are from a dipole-dipole survey "a" = 100 m, n = 1 to 4, filtered to incorporate all the readings.

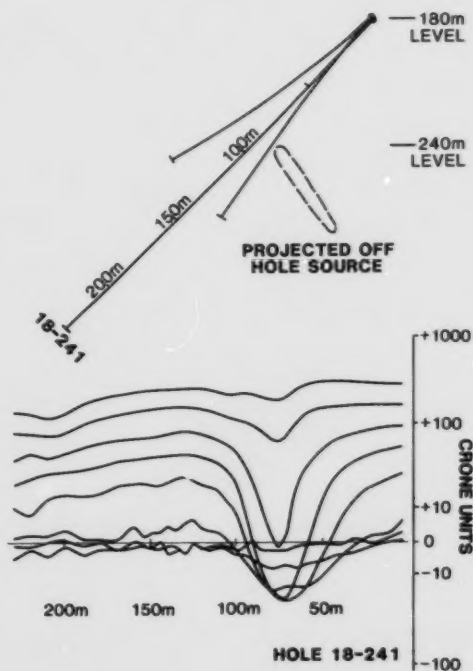


Figure 37.6. Crone Pulse EM response in an underground hole at Les Mines Selbaie.

itself, the discovery of lenses like this is extending the life of the mine.

VLF ELECTROMAGNETIC SURVEYS

CHETWYND, NEWFOUNDLAND, CANADA

Very Low Frequency Electromagnetic surveys (VLF EM) operating in the 15 to 25 kHz frequency range are being extensively used to assist in the mapping of rocks for gold exploration. The results of a VLF EM survey over the Selco-BP, Chetwynd gold deposit (now the Hope Brook Mine) are shown in Figure 37.7. This mine contains about 2 million ounces of gold. While geophysical surveys have played a role in the mapping of the area, the discovery was made by surface sampling of the plentiful exposed rock of the region (McKenzie 1986). The VLF EM instrument employed was the Geonics EM-16, measuring inphase and quadrature components as a percent of the primary field. The station used was Cutler, Maine, located to the southwest of the deposit. The map presents a generalized view of the geology along with the location of the ore horizon, and an adjacent barren pyrite zone known as the pyrite cap.

Conductors are indicated by a hatched line at inflections in the VLF EM response profiles. The strongest of these appears to identify the contact between mylonite to the northwest, and silicified rocks to the southeast. A small subsidiary response marks the pyrite cap. The strong response suggests the

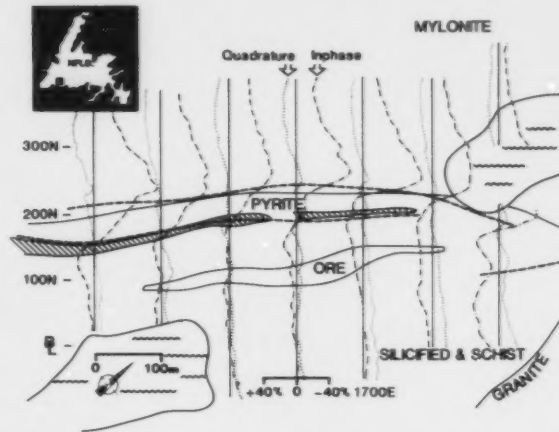


Figure 37.7. Profiles of VLF EM responses with geology over the Chetwynd gold deposit, Newfoundland. Broken lines indicate interpreted conductors.

identification of a structure at or near the contact. A break in topography seen at the top of Figure 37.8, at about 240N, implies a structure as well. The resistivity survey plotted in Figure 37.8 has identified a significant resistivity low and induced polarization high at 240N. Drilling of this response has revealed barren pyrite mineralization northwest of the previously known pyrite cap. Likely, both the structure and the sulphides come together to cause the

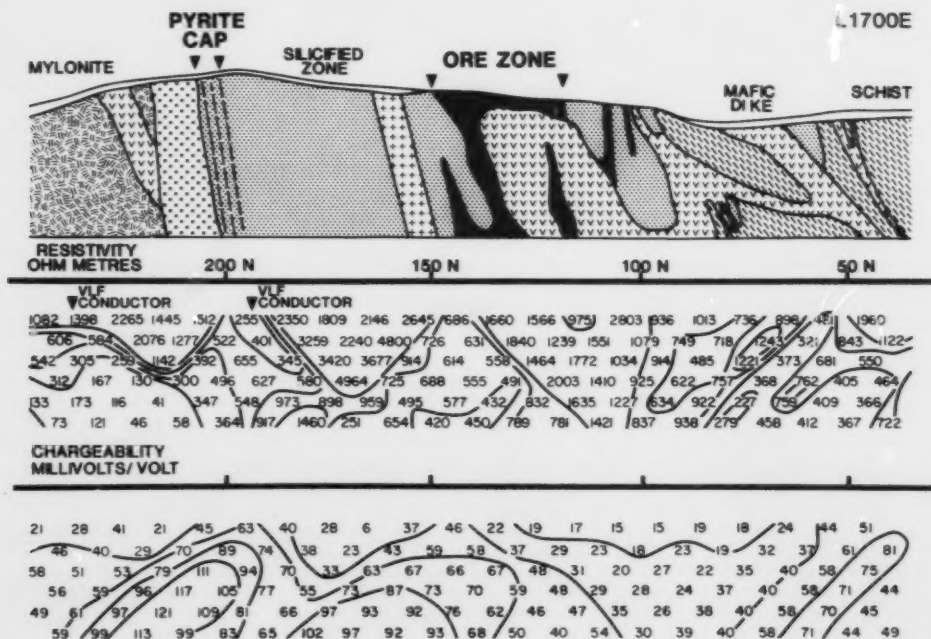


Figure 37.8. Geological Section along line 1700E, Chetwynd gold deposit (vertical and horizontal scales are common), with resistivity and IP responses from a dipole-dipole survey ("a" = 10 m).

VLF EM response. A small, narrow, resistivity low identifies the source of the weak VLF EM response at the pyrite cap. The lack of VLF EM response at the ore zone is explained by the appearance of the resistivities at about 145N on the line in Figure 37.8. The resistivity response here, is not as low as on either of the barren sulphide units. A lower percentage of sulphides in the ore zone is implied.

It is observed that VLF EM surveying has not been useful in identifying the ore zone. It has, however, identified a structure with sulphides which is an important marker regionally. Mapping of over 5 km of this structure has been assisted by VLF EM surveying.

INDUCED POLARIZATION AND RESISTIVITY SURVEYS

CHETWYND, NEWFOUNDLAND, CANADA

The Chetwynd Deposit lies in Ordovician volcanic and sedimentary rocks. The ore zone (Figures 37.7 and 37.8) is enclosed in a zone of heavily silicified rocks which may originally have been felsic volcanics. To the south, are schists of intermediate volcanic origin, while to the north lies a mylonite zone of felsic sedimentary origin. The mafic dikes seen in the section are the only magnetic rocks in the area. Although generally present throughout the ore zone, the dikes have been subjected to severe structural disruption, with limited individual horizontal and vertical continuity. Magnetic surveys (not shown), used to map these dikes, play no role in defining the ore zone, except to show the general distribution of the barren dikes.

Throughout the sequence of rocks, various quantities of pyrite are found. Pyrite occurs in very low amounts (less than 1 percent), to very high amounts (over 50 percent in the pyrite cap). Sulphides are a variable constituent of the ore zone, and although apparently a necessary condition for gold to be present, there is not a consistent correlation between the amounts of gold and sulphides.

It has been noted that neither VLF EM nor magnetic surveys were useful in mapping the ore horizon. Induced polarization (IP) has been successful in identifying the sulphides related to the ore zone, as well as the more extensively distributed sulphides in the area. IP and resistivity surveys employing 25 and 50 m "a" spacings of the electrodes, with dipole-dipole arrays, were carried out to map these sulphides. It was found, however, that the specific ore horizon was not identified by these surveys, because of the wide electrode spacings used.

A single experimental line, 1700E, was surveyed employing 10 m "a" spacings, in order to resolve the IP and resistivity response over the ore zone, and the surrounding rocks. Two instruments were used. A time domain, Huntect-Mark IV instrument col-

lected full waveform responses. A frequency domain, Phoenix-IPV-2 instrument collected phase IP data over five frequencies. It was found that at this level of detail (Figures 37.8, 37.9, and 37.10), responses could be correlated to geologically mapped details in the rocks.

Within the ore zone, from 120N to 150N, both a resistivity low and a resistivity high are present. Contrasts between pyrite and silicification content are suggested to be the source of these two responses. As much as 15 percent pyrite is noted at 145N in surface samples. Just north of the ore zone, reduced amounts of sulphides in the silicified zone are reflected in higher resistivities from 150N to 190N. The unsilicified schists to the south of the ore zone, are variously pyritized, and exhibit variable resistivities. The resistivity lows with VLF EM responses in heavier pyrite to the north have been noted above.

The IP response in Figure 37.8 shows four sources: one in the mylonite (the main VLF EM conductor), one in the pyrite cap, one in the northerly part of the ore zone, and one in the schists. Essentially all readings in the section are anomalous, indicating the widely sulphidized environment.

A question to be asked of the IP response is: is there anything about the response in the ore zone which distinguishes it from the adjacent non-ore responses? It is noted that the pyrite cap produces the largest IP response (over 120 millivolts/volt), while amplitudes in the ore zone (over 90 millivolts/volt) are somewhat smaller. Other responses from barren sulphides, north and south, are lower still. Nothing in these numbers suggests any uniqueness of the IP response of the ore zone.

The collection of the full waveform of the response has permitted the calculation of the Cole-Cole parameters (Pelton *et al.* 1978; Johnson 1984). With these (Figure 37.9), it was hoped to reveal some additional discriminating features. The chargeability section is repeated at the top of the figure. The time constant in the middle section shows some detail characteristics not evident in the chargeability section. In detail, higher time constants do not specifically identify with the higher chargeabilities, but rather flank them. Generally, however, the pyrite cap seems to generate higher time constants than the ore zone. In turn, the ore zone has higher time constants than either of the other responses, north or south. The Cole-Cole dispersion factor at the bottom of Figure 37.9 produces a response distribution similar to the chargeability section, with little to suggest some characteristic unique to the ore zone.

The phase angle responses for three of the five frequencies are plotted in Figure 37.10. The lowest and highest frequencies collected were 0.11 Hz and 9.0 Hz, respectively. Resistivities collected with these data (not shown) were very close in value to those of the time domain survey. Only $n=1$ to $n=4$

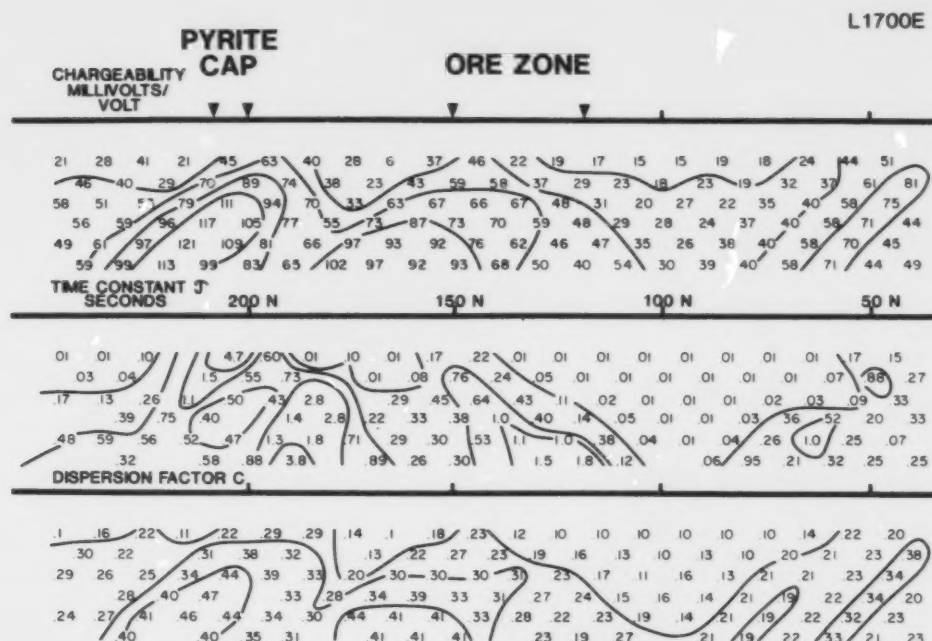


Figure 37.9. Section 1700E, Chetwynd gold deposit showing IP time domain survey results: total chargeability over the interval 60 to 1260 m sec., and the spectral parameters, time constant and dispersion factor.

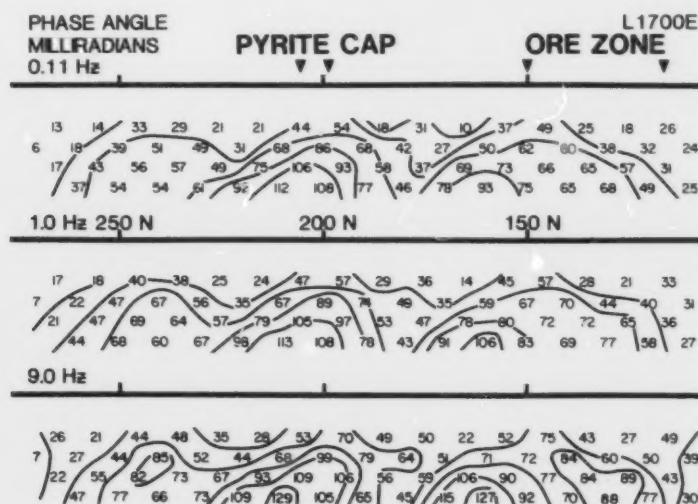


Figure 37.10. Section 1700E, Chetwynd gold deposit. IP frequency domain survey showing the phase angle response at three frequencies.

frequency data were acquired. The overall character of the IP effect is like that for the time domain survey. Some details change at higher frequencies, probably, as coupling effects begin to appear.

Hallof (1985) ascribed the variation in phase angle with frequency to the electrical size of sulphide grains. This suggests that for larger grain material,

the phase will not change significantly, while for smaller grain size, the phase angle will increase with increasing frequencies in the frequency range measured (Pelton *et al.* 1978; Wong and Strangway 1981).

An observable difference in the behaviour of the phase angle over the pyrite cap from that of the

other zones is noted. Phase angles generally do not change over the pyrite cap, while responses increase with frequency on all the other zones. The $n=4$ reading at 200N in the pyrite cap, from low to high frequency, is 108, 108, and 105 milliradians, while the $n=4$, 130N reading in the ore zone changes from 68, through 77, to 88 milliradians. This suggests that the sulphide grains are larger in the pyrite cap than elsewhere.

Reviewing all of the time and frequency domain IP data, it is seen that the pyrite cap, and not the ore zone provides the most distinctive response characteristics, either through larger amplitudes, or by the different behaviour of response with frequency. It can only be said of the ore zone that the northerly part of the zone is detected by an IP and resistivity response, but without the uniqueness of character which would call attention to itself over other responses in the area.

REFLECTION SEISMIC SURVEYS

WITWATERSRAND BASIN, SOUTH AFRICA

The use of reflection seismic techniques for mineral exploration in the South African Witwatersrand Basin is a revolution in mining exploration geophysics. The high cost of this work can be justified in part by the potential for new gold discoveries in the area. The total gold production from the Witwatersrand Basin, from the time of its discovery in 1886, to 1983, has been over 37 million kilograms, or nearly 1200 million ounces (Pretorius 1986). Some areas of the basin lend themselves to the application of standard petroleum type reflection seismic surveys. Beds, generally, are gently dipping and target depths may extend to 5000 m. Concerns expressed early in the development of the application, about obtaining reflections in the high velocity rocks of the basin (5000 to 6000 m per second), have not been borne out by the results. Good signals, and a variety of reflection events have been observed (Campbell and Peace 1984; see Paper 22, this volume).

Prior to the availability of seismic data, a lack of real geological information in parts of the basin inhibited appropriate sighting of drillholes. The cross-section, shown in Figure 37.11, was interpreted from limited drillhole information, with a good deal of guess work and reservation as to its accuracy. The nearest drillhole to the section was over 4 km away. The target strata are the Central Rand rocks, described as quartzites and conglomerates with minor shale. These carry almost all of the gold. Below this are the West Rand rocks, also described as shales, quartzites, and conglomerates. These are not a target for gold. Overlying the Central Rand are Ventersdorp volcanics and above this, the Karroo sequence of sediments and flat lying dolerite (diabase) sills.

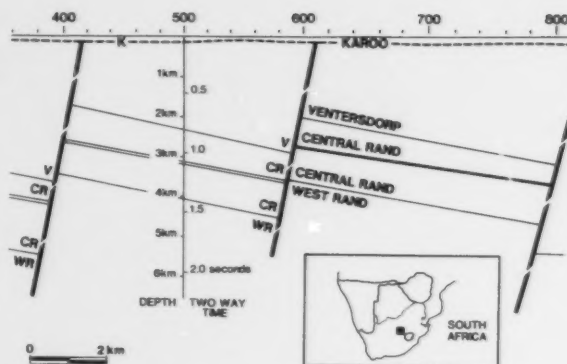


Figure 37.11. Geological section in the Witwatersrand Basin, South Africa, interpreted from drillholes in the vicinity. Numbers across the top are shot point numbers used for the seismic survey results shown in Figure 37.12. The two-way time with depth is derived from the acoustic velocity of the rocks in the section. The double line in the Central Rand suggests one of the gold-bearing reefs.

Seismic data show these rocks have distinctive characteristics. The Central Rand group, particularly, can show little reflection response, and is generally well contrasted with the overlying Ventersdorp and underlying West Rand. Both enclosing units show considerable "noisy" reflective responses. The Karroo sequence shows distinctive flat lying features, arising from sill-sediment contrasts.

All these features are evident in the seismic section shown in Figure 37.12. Most astounding, however, is the complete reversal of dip direction from the inferred dips in Figure 37.11. Further, the faults which were thought to occur either do not exist, or show no displacement on this cross-section. The transparent Central Rand rocks are most evident from 1.2 to 1.6 seconds from the left edge of Figure 37.12 to shot point 610. These rocks may be projected to the right of 610 using several reasonably well-defined reflection markers, so that the Central Rand rocks approach surface, but in a very different manner than is indicated by Figure 37.11.

Considerable detail appears on the section, including low angle faults dipping to the right (dashed lines) and wedges of different material identified as closed blocks between solid lines. One such wedge cutting into the quiet Central Rand response with an arcuate upper boundary is seen from 1.5 to 1.8 seconds from shot points 470 to 600. The type of rocks in this wedge are not known, although their very reflective, noisy character suggests West Rand.

Seismic sections such as in Figure 37.12 make possible the selection of new target areas not previously recognized. Confirmation or modification of interpretations from subsequent drilling can generate a complete re-thinking of the potential for gold in a target area.

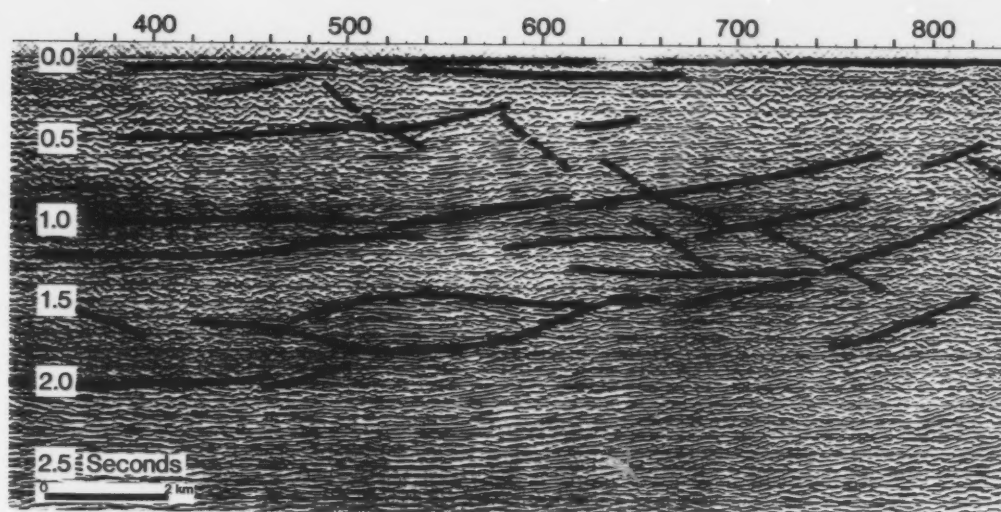


Figure 37.12. Seismic section with interpretation along the same line as in Figure 37.11. Numbers at the top are the shot points. The vertical scale is the two-way return time. Solid lines are interpreted contacts, dashed lines are interpreted faults.

CONCLUSIONS

Geophysical surveys have been shown in a broad range of applications in the search for gold. In its most useful and appropriate application, geophysical surveys become part of, and an extension to, geological mapping processes. Regional and detail magnetic and electromagnetic surveying extend and refine existing geological mapping. It has been noted that because of the small amounts of gold in the rocks, the direct detection of gold by geophysical methods is not feasible. The direct detection of associated minerals using induced polarization, electromagnetic and magnetic surveys, however, has been shown to be effective. Finally, it is possible to adapt an old geophysical technique to a new application, as in the Witwatersrand reflection seismic survey. This example may well be a guide for explorationists to follow in other environments.

Significant problems remain for the use of geophysical methods in gold exploration. Reports are common that the application of geophysical methods has not contributed to the exploration and development of some deposits. While occasionally this may signify the failure to apply the appropriate method, some gold deposits such as the low sulphide deposits, do not lend themselves to direct detection by standard approaches. Continued study of the physical response characteristics of the geological problem should improve the application of geophysics in the search for gold.

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38. The Geophysical Response of The Red Dog Deposit

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ABSTRACT

"Red Dog" is a shale-hosted, polymetallic massive sulphide deposit situated in the Western Brooks range in Alaska. It is a world-class base-metal deposit with published reserves of 77 million metric tons at an average grade of 17 percent zinc, 5 percent lead, and 82 g/t silver. The age of the mineralization and associated shale host ranges from Lower Mississippian to Middle Pennsylvanian. The abundance of organic debris, fossilized worm tubes, and silica suggests the deposit was formed in an environment similar to modern submarine hydrothermal vent localities in spreading sea floor centres such as those in the Pacific.

The Red Dog Deposit was surveyed using numerous geophysical techniques including INPUT, aeromagnetics, IP, resistivity, CS-AMT, UTEM, HLEM, and gravity. As well, several drillholes were logged with IP and resistivity. Generally, any one method delineates the shallow portion of the deposit.

The average intrinsic bulk resistivity of the main deposit ranges from 20 to 120 ohm-metres with a corresponding chargeability of approximately 25 milliseconds. There are distinct zones where the intrinsic resistivity is much lower with higher chargeability; however, these zones are not continuous throughout the deposit. The deposit is not a strong conductor, but is easily detectable because locally, the surrounding rocks are resistive and have few spurious conductors. The overall lack of strong conductors within and proximal to the deposit is possibly due to the fact that the rocks are unmetamorphosed.

INTRODUCTION

"Red Dog" is a shale-hosted polymetallic massive sulphide deposit. It is a world-class base-metal deposit with published reserves of 77 million metric tons at an average grade of 17.1 percent zinc, 5 percent lead, and 82 g/t silver. The age of the shale host and mineralization ranges from Mississippian to Middle Pennsylvanian. The deposit is located 145 km north of Kotzebue, Alaska (Figure 38.1) in the DeLong Mountains of the western Brooks Range.

The Red Dog Deposit was first visited in 1968 by Dr. Irving Tailleux of the U.S. Geological Survey at the recommendation of Bob Baker, a local bush pilot, who observed the colour anomaly from the air and used it as a navigation aid. The mineral occurrences were further reported by the U.S. Bureau of

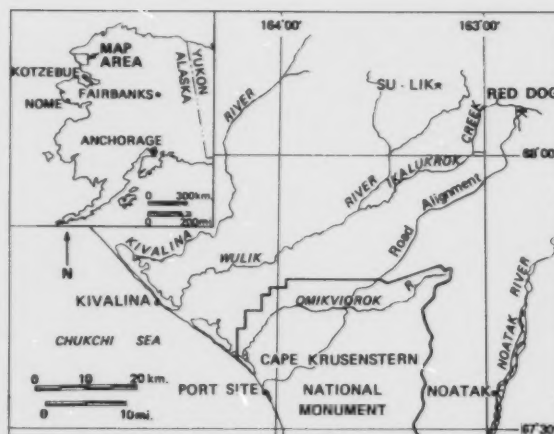


Figure 38.1. Location map for the Red Dog Deposit, Alaska, USA.

Mines in 1975 following their initial evaluation of the area for a proposed park. Cominco American Incorporated commenced exploration of the region at that time.

The U.S. Geological Survey and several other companies have mapped, sampled, and run geophysical surveys on the deposit. Cominco's initial geophysical surveys on the Red Dog Deposit were performed under an access permit in 1977, but the majority of the work was done in the early 1980s in conjunction with drilling and geological mapping. The objectives of Cominco's geophysical program were to delineate the lateral and downdip extent of the deposit as an aid in the drilling program, and to catalogue the response of the deposit using different systems to guide future exploration in the district. The geophysical methods run by Cominco American Incorporated on the deposit include gravity, INPUT, induced polarization (IP) and resistivity, CS-AMT, UTEM, and HLEM.

The deposit's geophysical response and the effectiveness of these different systems are discussed in this paper.

GEOLOGY

REGIONAL GEOLOGY

The region around the deposit consists of many (eight presently identified) stacked and folded structural slices or allochthons. The six structurally lowest are composed of Paleozoic and Mesozoic sedimen-

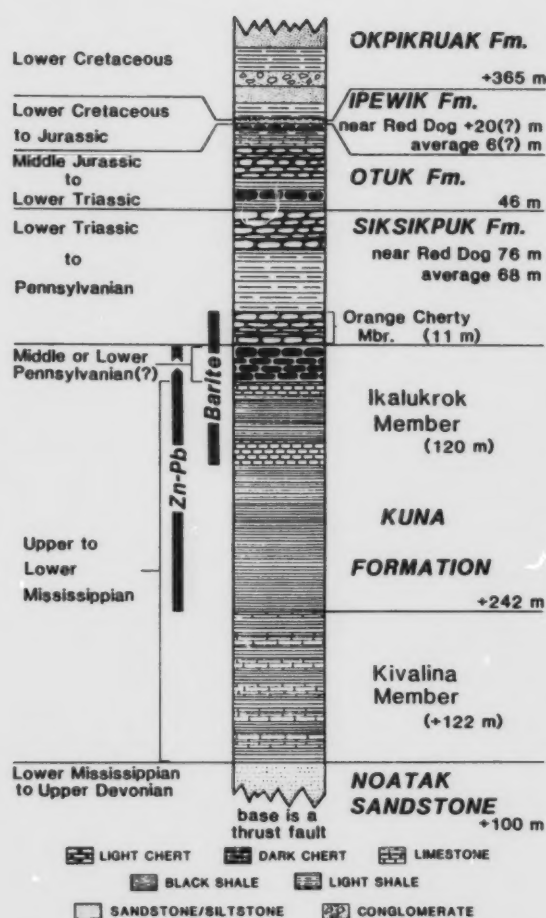


Figure 38.2. Stratigraphic section for the Red Dog Deposit, Alaska, USA, (from Moore *et al.* 1986).

tary rocks (Tailleur *et al.* 1966; Tailleur *et al.* 1967; Martin 1970; Ellersieck *et al.* 1979). The two upper allochthons also contain Jurassic or older mafic and ultramafic igneous rocks. They are all separated by undulating thrust surfaces and each may contain one or more repetitious sequences (Mayfield *et al.* 1983a). The Red Dog Deposit is contained within the upper part of the lowest allochthon (Brooks Range) as recognized by Mayfield *et al.* (1983b), or the next to lowest allochthon as recognized by Moore *et al.* (1986).

The Brooks Range allochthon is composed of clastic and chemical sedimentary rocks ranging in age from Upper Devonian to Lower Cretaceous (Chapman *et al.* 1964; Mayfield *et al.* 1983b; Moore *et al.* 1986). Figure 38.2 shows the relationship of the deposit to the stratigraphy. It is contained within the Ikalukrok Member of the Kuna Formation. The Ikalukrok Member ranges up to 212 m thick, and consists of chert, and poorly laminated to

well-indurated, sooty black shales, with high silica content. Locally at the deposit, the chert and black shales grade laterally into sulphide-bearing barite and massive sulphides.

GENERAL GEOLOGY OF DEPOSIT

The Red Dog Deposit consists of polymetallic sulphide rock, barite rock, and silica rock. For simplicity, the sulphide rock has been divided into "massive sulphide rock" (greater than 70 percent sulphides) and "semi-massive sulphide rock" (greater than 40 percent but less than 70 percent sulphides). Sulphide-bearing (greater than 1 percent and less than 40 percent sulphides) is used as a modifier in describing mineralized barite, silica rock, and shale (Moore *et al.* 1986). The sulphide mineralization consists of sphalerite, pyrite, marcasite, and galena, with traces of chalcopryrite and pyrrhotite. Most of the sulphides are fine grained. Silica is the most abundant gangue and barite is prevalent. Clastic sediments and some organic debris are also found intermixed in some areas with the sulphides. Chert is widespread and forms blebs and patches and is generally dark due to the inclusion of organic matter (Moore *et al.* 1986). Pyrobitumen also is commonly noted. Dark chert also forms the walls of cylindrical structures postulated to be worm tubes (Plahuta 1978).

The surface geology in the vicinity of the main Red Dog Deposit and the satellitic Hill Top Deposits is shown in Figure 38.3. The main zone is exposed over a 1.5 km² area while the smaller "Hill Top" covers only a 0.51 km² area. There is evidence of stacking of the section. The drilled thickness of the mineralization varies between 8 and 158 m. The structural footwall of the deposit is the thrust contact between the Brooks Range allochthon on top, and the Wolverine Creek allochthon on the bottom (Moore *et al.* 1986).

GENESIS

Observers have postulated that the deposit formed in an environment similar to present hydrothermal areas, such as that found in the Guaymas Basin in the Gulf of California (Edmond 1982), where there is replacement of soft sediments by sulphides, or the spreading sea floor areas in the Pacific. The Pacific areas contain "Black Smokers" (consisting of sulphide chimneys and sulphide exhalites), high heat flow, and communities of large clams, mussels, and vestimentiferan worms (Grassle 1982). J.T. Plahuta (Geologist, U.S. Bureau of Mines, personal communication, 1977) was the first to recognize the presence of fossilized worm tubes at the Red Dog Deposit. The paleoenvironment for the Red Dog Deposit would not have to be identical to either setting but, similar to modern environments, high heat flow, localized plant and animal communities, rapid emplacement of sulphides, as sulphide chimneys, ex-

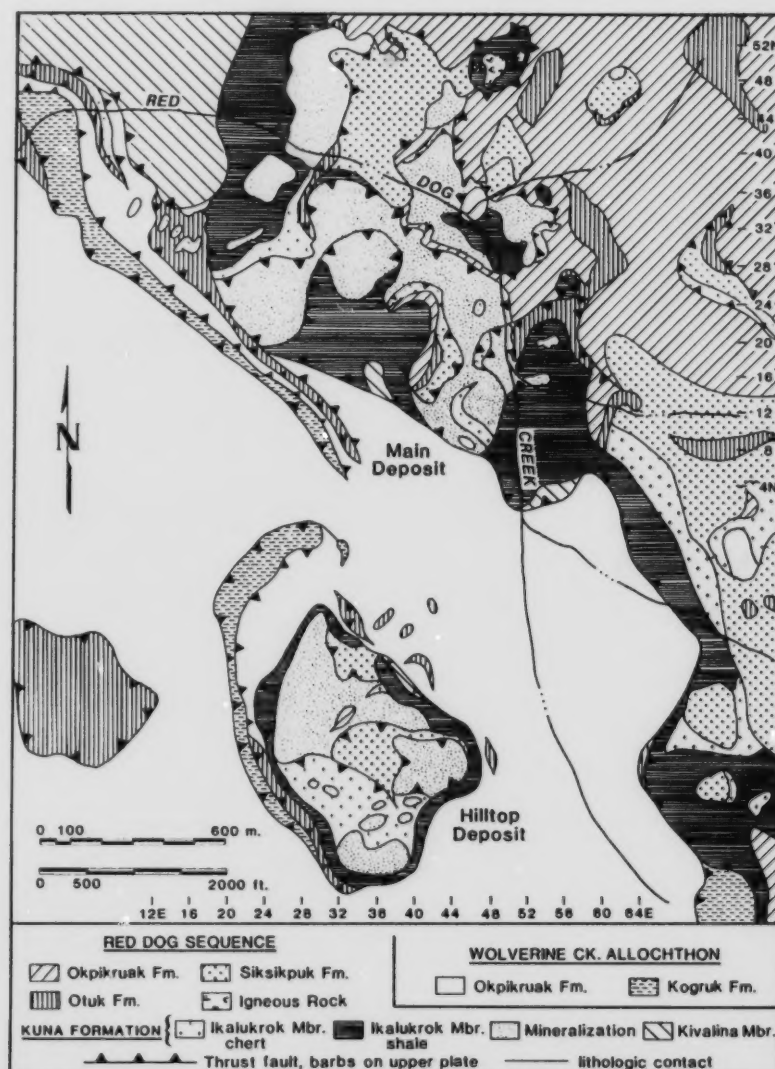


Figure 38.3. Generalized geology map of the Red Dog Deposit, Alaska, USA (from Moore et al. 1986).

halites, and/or as soft sediment replacement, and rapid burial of exposed sulphides to prevent oxidation probably occurred.

The sulphides generally have a fine-grained texture and an overall lack of intergrowth of crystals. The presence of organic carbon and pyrobitumen indicates that the deposit was never subject to high temperatures and pressures. Thus, sufficient heat and pressure were not available to metamorphose the organic carbon to graphite or to substantially recrystallize the sulphides, especially the galena and pyrite, into a large electrically interconnected mass. There is evidence of localized crystalline growth such as one might expect to occur near individual vents and/or sulphide chimneys due to locally elevated temperatures.

SULPHIDE DISTRIBUTION

The geological map (see Figure 38.3) is the base map for all subsequent maps. Figure 38.4 is a contour map of the foot-percent combined zinc and lead for the deposit showing the location of the east-west geophysical lines 16N, 24N, and 32N. The 2500-foot-percent (Zn+Pb) contour lies within the limits of the 1985 model of the open pit with the maximum value over 18 000 foot-percent (Zn+Pb).

Three "grade sections", Figures 38.5, 38.6, and 38.7, were produced to show the relationship between the distribution of economic sulphides and the responses of different geophysical surveys. The distribution of pyrite is known, but is not presented here. The ultimate goal was to trace economic mi-



Figure 38.4. Contoured foot-percent zinc + lead map for the Red Dog Deposit, Alaska, USA.

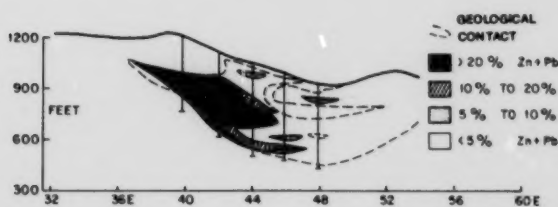


Figure 38.5. Zinc + lead grade section, Line 16N, Red Dog Deposit, Alaska, USA.

neralization. This is not in disregard to the fact that pyrite contributes to the overall conductance of the deposit. There are large areas containing over 15 percent iron; however, the iron content is highly variable. Figure 38.8 shows the vertical distribution for one hole, MAC-19. The amount of iron sulphides is generally about equal to that of the zinc or

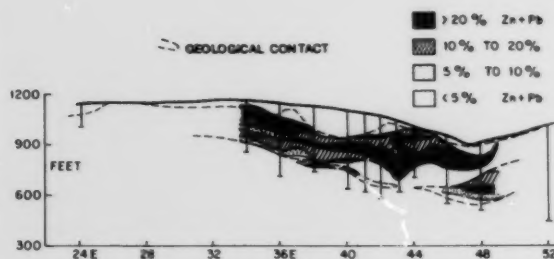


Figure 38.6. Zinc + lead grade section, Line 24N, Red Dog Deposit, Alaska, USA.

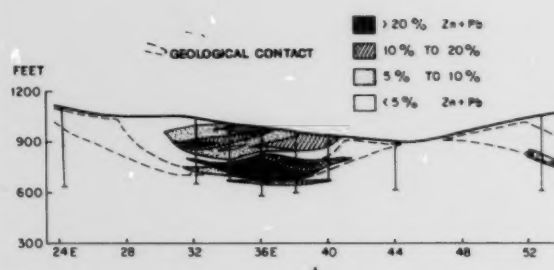


Figure 38.7. Zinc + lead grade section, Line 32N, Red Dog Deposit, Alaska, USA.

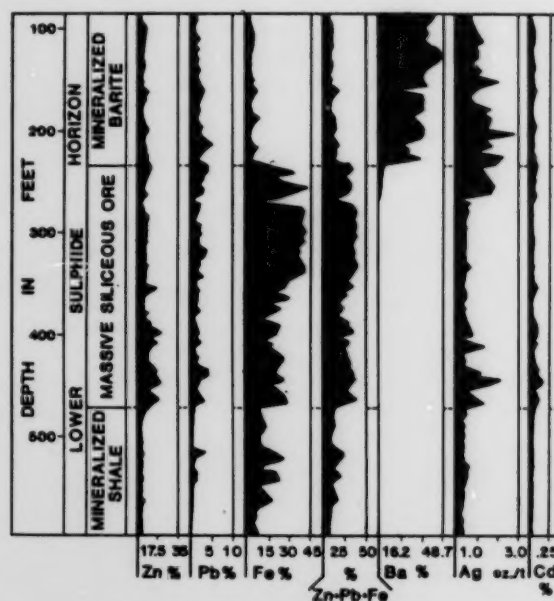


Figure 38.8. Vertical metal distribution through lower sulphide horizon as seen in MAC-19 at 52N, 36E, Red Dog Deposit, Alaska, USA (from Moore 1986).

lead. There is some zoning present in this drillhole; however, this is not necessarily typical.

GEOPHYSICS

The deposit was surveyed using many different geophysical methods. The purpose of the surveys was to help delineate the deposit and to evaluate the applicability of different techniques and methods in the exploration for other similar deposits.

AIRBORNE GEOPHYSICS

Cominco American Incorporated has had the Red Dog Deposit flown two separate times with fixed wing INPUT systems. In 1981, Geotrex Limited (Geotrex Limited 1981) flew it using a Mark V system with a 1.2 millisecond pulse width, and in 1984, Questor flew it using a Mark VI system with a 2 millisecond pulse width. The terrain is marginal for a fixed wing survey.

Both surveys were forced to fly in a northeast-southwest direction subparallel to the elongation of the deposit. The ground clearance varied along flight lines from 450 to greater than 700 feet. As a result, anomalies have distorted shapes, and interpretations of conductivity-thickness are unreliable.

The two surveys had essentially the same results, but only the 1981 survey was compiled on a topographic base and will be presented in this paper. Figure 38.9 is a compilation map of the INPUT anomalies and Figure 38.10 is an INPUT profile showing the typical results for the Hill Top Deposit (MC-3) and the Main Deposit (MC-5). Table 38.1 contains the parameters of that profile as well as conductivity-thicknesses calculated using a vertical 1/2 plane model. These values range over a wide span due to effects of high noise. Table 38.1 also contains the timing for the channel for the Mark V system.

In general, the 1981 anomalies associated with mineralization have small early channel responses that decay rapidly in the later channels. None of the anomalies had six channel responses and the average first channel response over the deposit was less than 216 ppm. The estimated conductance using the vertical 1/2 plane model ranged between 3 and 25 mhos for anomalies associated with mineralization.

In comparison, the 1984 survey detected 4 to 5 channel anomalies with interpreted conductances of 5 to 7 mhos north of Red Dog Creek, while immediately south of Red Dog Creek there are 2 and 3 channel anomalies with interpreted conductances ranging from 3 to 25 mhos. Farther south in the vicinity of the Hill Top Deposit, there are 3 to 6 channel responses and interpreted conductances of 4 to 38 mhos. The deposit in the simplest terms can be thought of as an oblate ellipsoid, therefore the calculated conductivity thickness values using a vertical 1/2 plane model are probably overestimated.

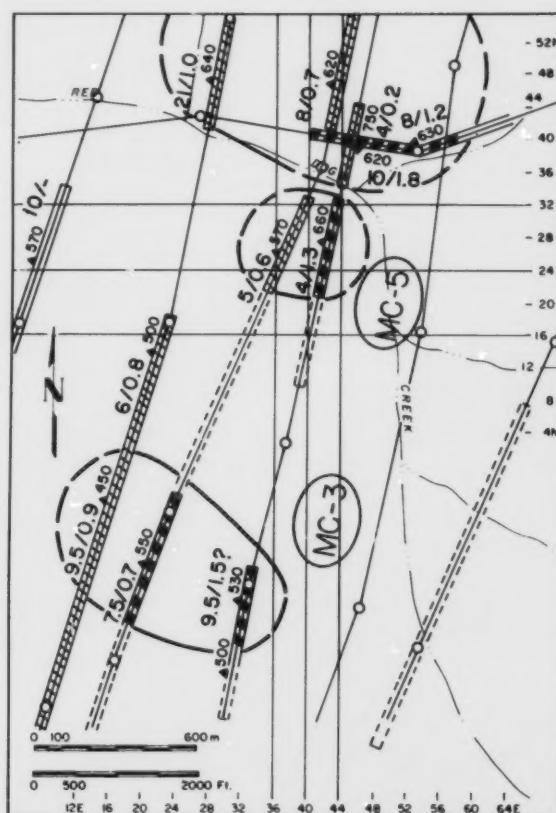


Figure 38.9. Input anomaly map for the Red Dog Deposit, Alaska, USA.

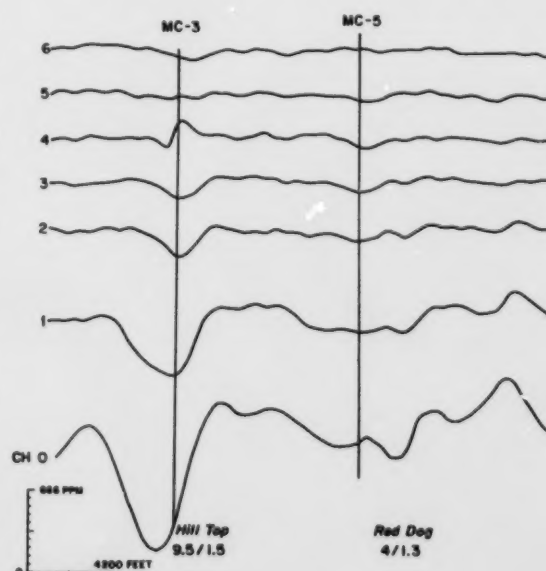


Figure 38.10. Input profile for Red Dog Deposit, Alaska, USA.

TABLE 38.1. MARK V INPUT TIMING.

MARK V INPUT TIMING		
Channel	Gate Centre μsec.	Gate Width μsec.
0	160	200
1	260	200
2	460	200
3	710	500
4	960	400
5	1360	600
6	1860	600

INPUT RESPONSE									
Area	Channel (ppm)						Conductance (mhos)*	Depth (feet)	Elev. (feet)
	1	2	3	4	5	6			
Main	216	100	67	100	67	-	3-25**	300	660
Hill Top	466	233	133	100	67	83	9-38**	250	530

* Conductance values calculated for a vertical 1/2 plane model.

** The higher values are subject to error due to noise on the later channels.

AEROMAGNETIC MAP

Figure 38.11 is an aeromagnetic map compiled from the 1981 INPUT survey. As would be expected for this type of deposit, little or no magnetic anomaly can be associated with the deposit. The response is dominated by a strong regional anomaly associated with basement rocks. The measured susceptibility on selected mineralized samples range from 0 to 55 x 10⁻⁶ cgs.

GROUND GEOPHYSICS

Induced Polarization and Resistivity

The deposit was surveyed using time domain IP and resistivity techniques employing a dipole-dipole electrode configuration. The resistivity values are reported in ohm-metres and chargeability in milliseconds. The timing used was a standard two second on time. The electrode separation or "a" spacing was generally 400 feet, although several areas were surveyed using an electrode spacing of 100 feet. Little effects from electromagnetic coupling were noted. The larger dipole maximized penetration and the shorter electrode interval was useful to resolve the large resistivity and chargeability discontinuities within the mineralized zone.

LINE 16N (Figures 38.5 and 38.12)

This line passes over the southern edge of the highest concentration of mineralization, exceeding 10 000 foot-per-cent combined Zn+Pb at station 42E. The resistivity low on the line is centred near station 44E and probably reflects the shallow mineralization that is shown on the grade section. The response is interpreted to be from a shallow tabular body near 44E with possibly two other weaker zones, one at depth to the west around 38E, the other around station 52E to the

east. The chargeability high is displaced to the east of the main mineral occurrence. The response is consistent with a shallow, wide tabular body.

LINE 24N (Figure 38.6 and 38.13)

The mineralization is wider on this line than the previous line extending from station 34E to 49E. The pattern in the resistivity response is indicative of a narrow feature centred between 44E and 48E. This probably reflects only the shallowest portions of the mineralization. There are some topographic effects seen in the section.

The patterns in the chargeability response are indicative of a narrow feature in the same location as the resistivity low. The mineralization is generally represented by values of over 10 milliseconds.

LINE 32N (Figure 38.7 and 38.14)

The main concentration of economic mineralization extends from station 30E to 42E. The pattern of the response resembles that of a shallow tabular body, but the magnitude of the values are not consistent with the abundant mineral content.

The two small highs of greater than 25 milliseconds are directly related to shallow surface mineralization. The wide zone of greater than 15 milliseconds is related to disseminated sulphides.

LINE 30N (Figure 38.15)

There is no corresponding grade section for this line; it was surveyed using 100-foot electrode spacings. This was the first geophysics done on the property (Van Blaricom 1977). The data exhibits several features worthy of noting. On this more detailed survey, the resistivity and chargeability variations are more pronounced. The mineralization extends from station 40E to 48E corresponding to values of less than 200 ohm-metres. Superimposed upon this is a localized low apparent resistivity.

The IP response is a wide anomalous zone, with chargeability values over 25 milliseconds. Superimposed upon this is the response of a narrow zone with much higher values.

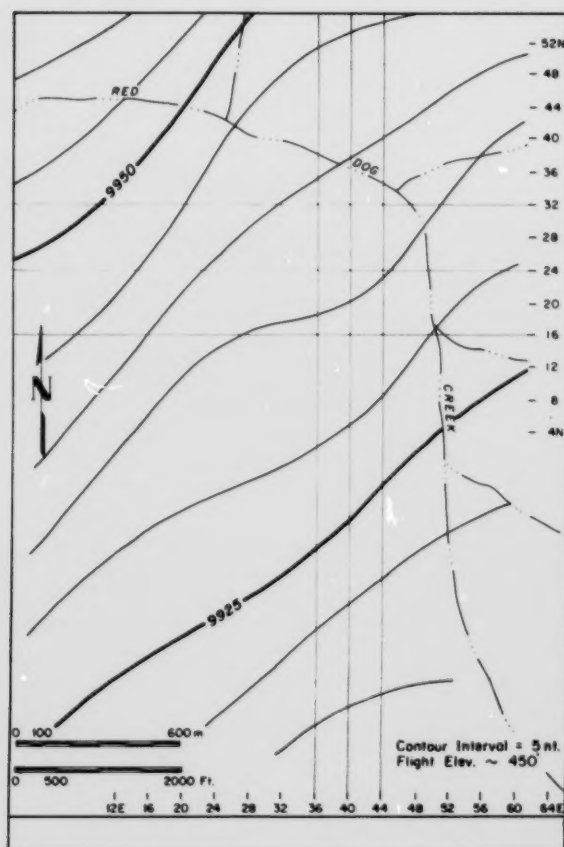


Figure 38.11. Airborne magnetics map for Red Dog Deposit, Alaska, USA.

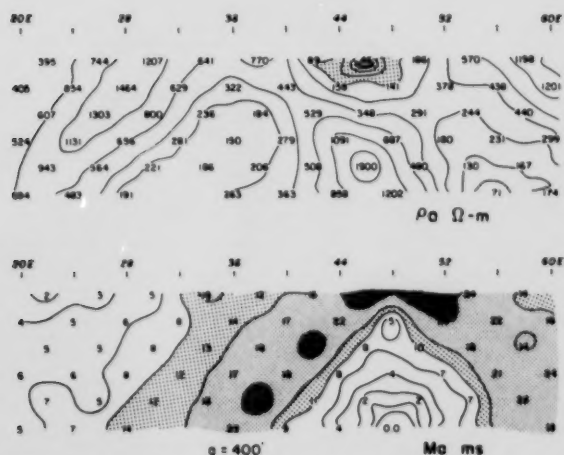


Figure 38.12. Induced polarization and resistivity pseudo section, Line 16N, Red Dog Deposit, Alaska, USA.

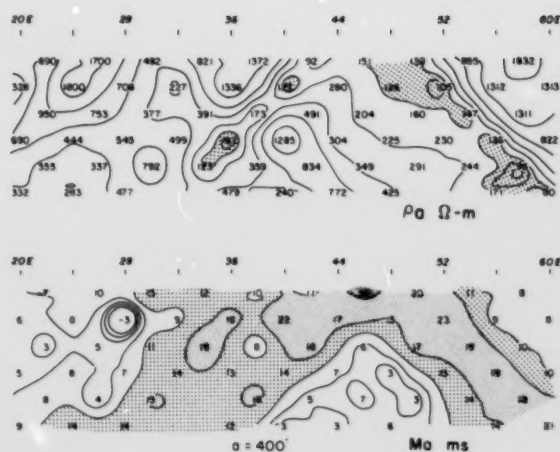


Figure 38.13. Induced polarization and resistivity pseudo section, Line 24N, Red Dog Deposit, Alaska, USA.

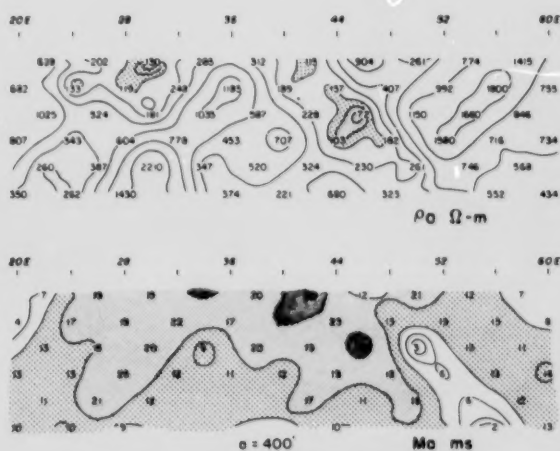


Figure 38.14. Induced polarization and resistivity pseudo section, Line 32N, Red Dog Deposit, Alaska, USA.

The shorter electrode interval accentuates shallow, narrow, and shorter features.

The resistivity and chargeability contour maps (Figures 38.16 and 38.17) show the continuity between lines. Generally, apparent resistivity values of less than 150 ohm-metres or chargeability values greater than 15 milliseconds correlate with greater than 2500 combined foot-percent zinc and lead (O'Connor 1983). The Hill Top Deposit is clearly anomalous with this type of presentation.

The results of this survey and others in the area suggest that IP and resistivity surveys are useful geophysical exploration techniques to delineate and detect shallow Red Dog-type occurrences.

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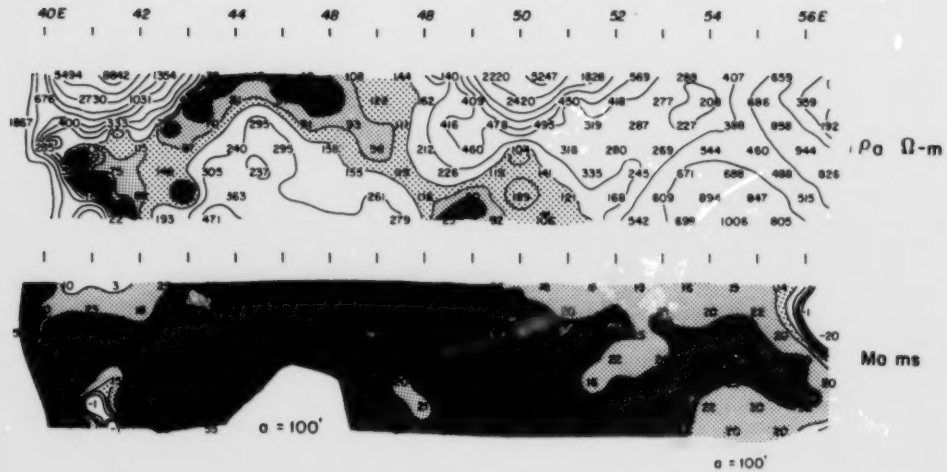


Figure 38.15. Induced polarization and resistivity pseudo section, Line 30N, Red Dog Deposit, Alaska, USA.

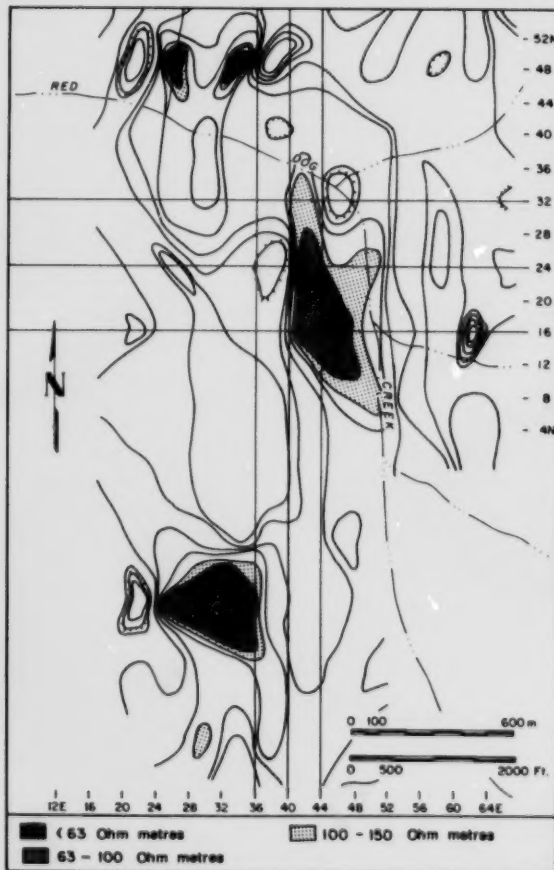


Figure 38.16. Contoured ρ_a — dipole-dipole survey, $N=1$, $a=400'$, for the Red Dog Deposit, Alaska, USA.

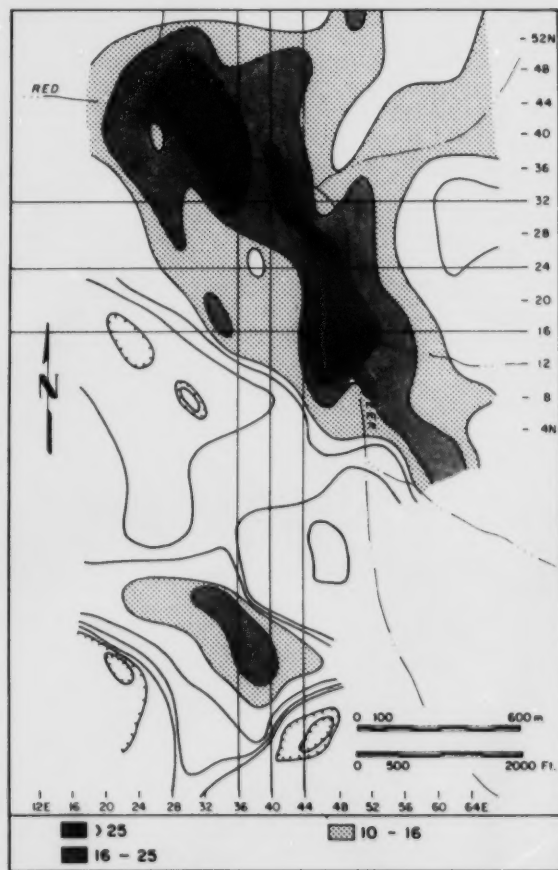


Figure 38.17. Contoured apparent chargeability, dipole-dipole I.P. Survey, $N=1$, $a=400'$ for the Red Dog Deposit, Alaska, USA.

Horizontal Loop Electromagnetics

The deposit was surveyed using frequencies of 3555 Hz, 1777 Hz, and 888 Hz with coil separations of 800 and 400 feet. The survey was designed to maximize the induction number because of the low response parameters. The 800-foot data are erratic due to the complexity and geometry of the deposit with respect to the coil separation (O'Connor 1983) and are not presented here.

LINE 24N (Figures 38.6 and 38.18)

The response departs somewhat from a classical response in either a flat prism or vertical feature. The ratios of in-phase to quadrature and the loss of low frequency response suggest that the feature is weakly conductive. The width of the response and its shape indicate a complex feature which has a width of over 200 feet with its eastern edge near station 49E and a westerly dip.

LINE 32N (Figures 38.7 and 38.19)

The patterns in the data suggest the response from a complex horizontal prism. The response from both the in-phase and quadrature for the three frequencies implies two weakly conductive shallow flat plates. The interpreted edges of the plates would be close to the limits of the main mineralized zone.

The response from the HLEM survey supports a gently dipping complex zone with a bulk conductivity-thickness which ranges from 1 to 5 mhos. The data indicate that an

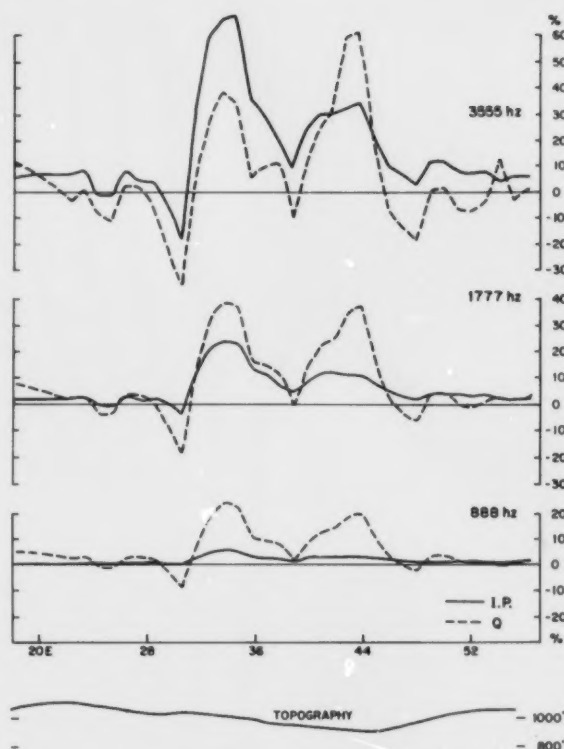


Figure 38.19. HLEM profile, Line 32N, 400' coil spacing, for the Red Dog Deposit, Alaska, USA.

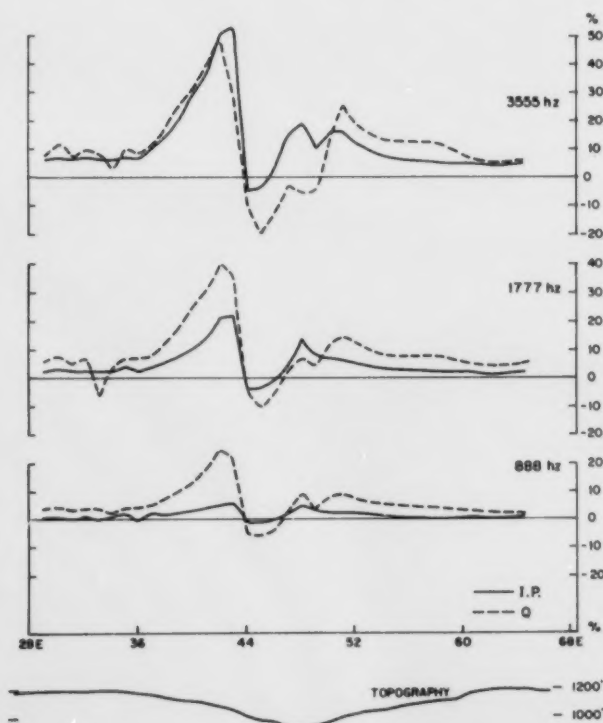


Figure 38.18. HLEM profile, Line 24N, 400' coil spacing, for the Red Dog Deposit, Alaska, USA.

HLEM survey would be a usable technique for deposits of this type. However, the surveys on other similar deposits suggest that the technique has depth limitations due to the poor response parameters of the targets.

Gravity

A gravity test was run on the property by Cominco American Incorporated in conjunction with a survey done by D.F. Barnes of the U.S. Geological Survey. The combination of the two data sets is presented as contoured data only (Figure 38.20); no profiles were constructed.

There is a well-formed anomaly of approximately 27 mg associated with the main deposit. The -40.5 mg contour corresponds well with the 5000 foot-percent combined Zn+Pb contour. There is a large +4.5 mg anomaly to the north; this is in response to both lead and zinc sulphides as well as to abundant shallow barite. Only two lines were run on the Hill Top Deposit.

Cominco American Incorporated made no excess mass calculations on this data; however, Barnes (Barnes and Morin 1984) did. Barnes calculated an excess mass of 22 million tons for the anomaly south of Red Dog Creek using Gauss' theorem (Nettleton 1976). He collected 18 hand specimens of mineralization and measured densities which ranged from

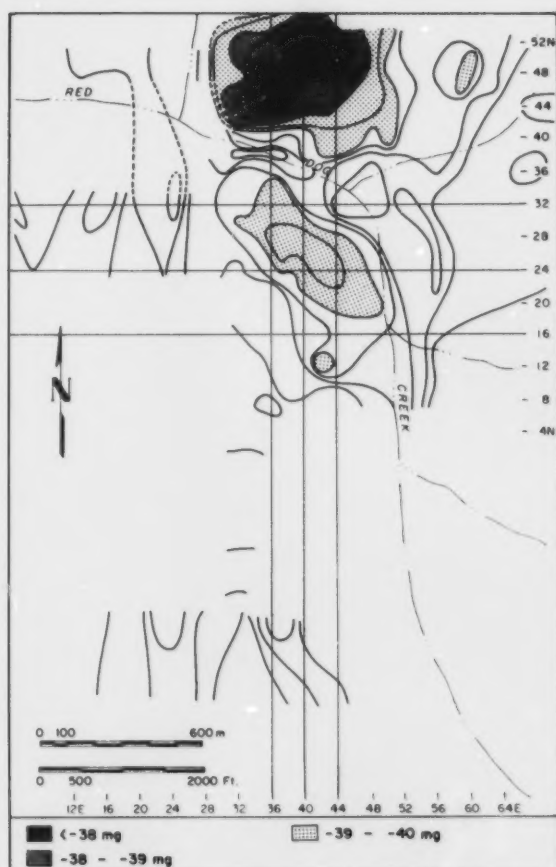


Figure 38.20. Contoured simple bouguer gravity map of the Red Dog Deposit, Alaska, USA.

2.86 to 3.99 gm/cm³ with an average of 3.81 gm/cm³. These results yielded an estimated 66 million tons of ore. These results are remarkably accurate considering the limited field time spent on the project. The results of the gravity survey indicate that this survey technique should be considered if doing exploration for similar shallow deposits.

UTEM

The deposit was surveyed in 1982 using the UTEM system. The purpose was to determine the applicability of the UTEM system for deposits of this type (Eadie 1982). The primary frequency employed was 30.496 Hz with data recorded from 16.3 μ seconds to 16.6 milliseconds in 10 logarithmic-spaced windows. The transmitting loop was located to the west of the main deposit; however, several lines were run using a loop to the east. All lines gathered H_z information and several lines were run with H_x and H_y information recorded. All channels were normalized to the last channel (1). The data were interpreted by E.T. Eadie of Cominco Limited, and selected por-

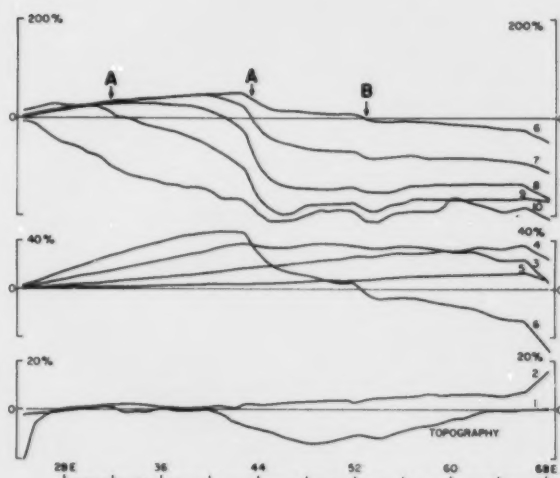


Figure 38.21. UTEM profile, Line 16N; H_z CH-1 normalized; T_x to west (602); for the Red Dog Deposit, Alaska, USA.

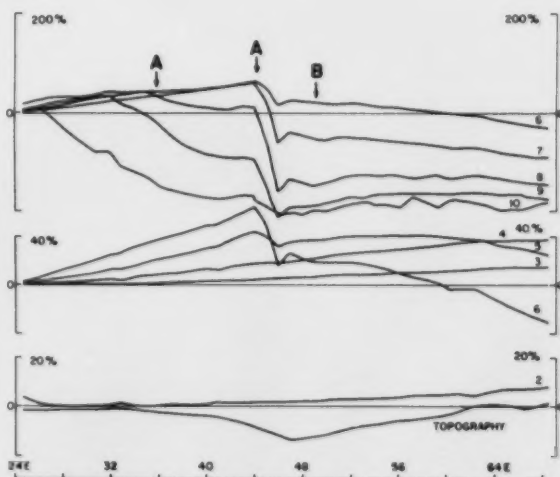


Figure 38.22. UTEM profile, Line 24N; H_z CH-1 normalized; T_x to west; for the Red Dog Deposit, Alaska, USA.

tions modeled using the plate modeling program developed by the University of Toronto.

Line 16N (Figures 38.5 and 38.21)

Several features are noticeable in the profiles. The main inflection point "A crossover" lies well within the main sulphide zone at the edge of the upper plate of mineralization occurring around station 44E. The response of the later channels decays quite rapidly, similar to the INPUT response.

Line 24N (Figures 38.6, 38.22, 38.23, 38.24, and 38.25)

Figures 38.21 and 38.24 contain the H_z data from two different transmitter locations. There is a major crossover

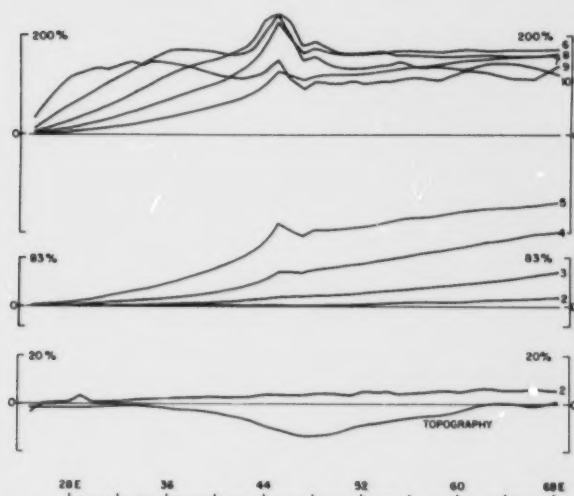


Figure 38.23. UTEM profile, Line 24N; H_x ; T_z to west; for the Red Dog Deposit, Alaska, USA.

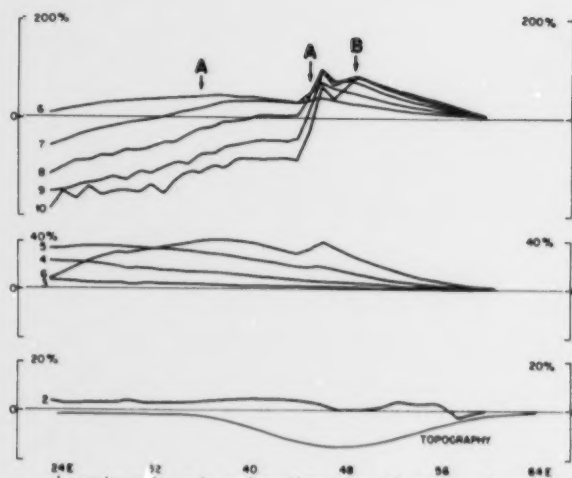


Figure 38.25. UTEM profile, Line 24N; H_2 CH-1 normalized; T_x to east; for the Red Dog Deposit, Alaska, USA.

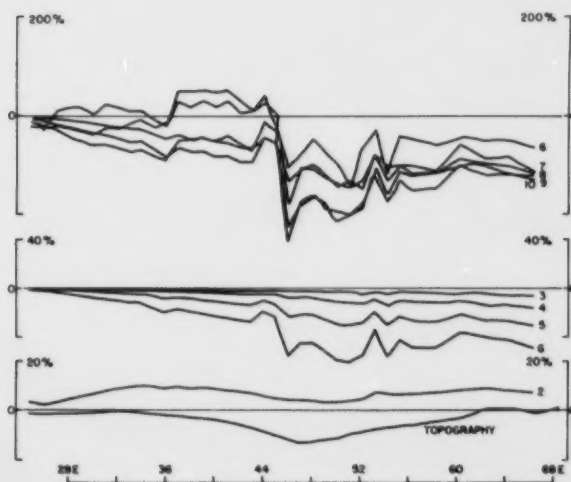


Figure 38.24. UTEM profile, Line 24N; H_y ; T_x to west; for the Red Dog Deposit, Alaska, USA.

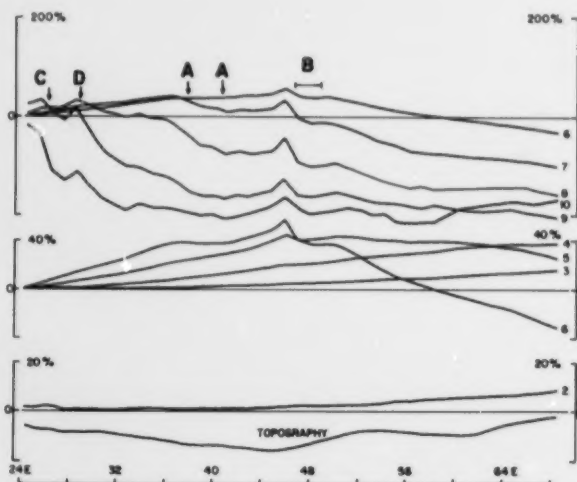


Figure 38.26. UTEM profile, Line 32N; H_2 CH-1 normalized; T_x to west; for the Red Dog Deposit, Alaska, USA.

near station 44E; this correlates to the the eastern edge of the shallow portion near the centre of mineralization; however, the western edge of the deposit responds poorly. The later channel response is rather weak.

The H_x and H_y data are also presented for the transmitter locations to the west. The H_x shows a positive bump over station 44; this is in agreement with the H_z data; both are indicative of a narrow feature. The H_y data is indicative of a limited strike length to the conductor at station 44E and the presence of other lateral discontinuities.

Line 32N (Figures 38.7, 38.26 and 38.27)

The line was run using two separate transmitter locations. The centre of the mineralization is represented by a weak crossover near station 36E. The response from the edge of the mineralization is also weak. The response from the main zone decays rapidly in late times.

The interpretation map for the UTEM is shown in Figure 38.28. Several values for the conductivity thickness are also shown, which agree with those from other methods. The UTEM is a fast exploration method for deposits of this type. The response of the deposit decays rapidly and little response is

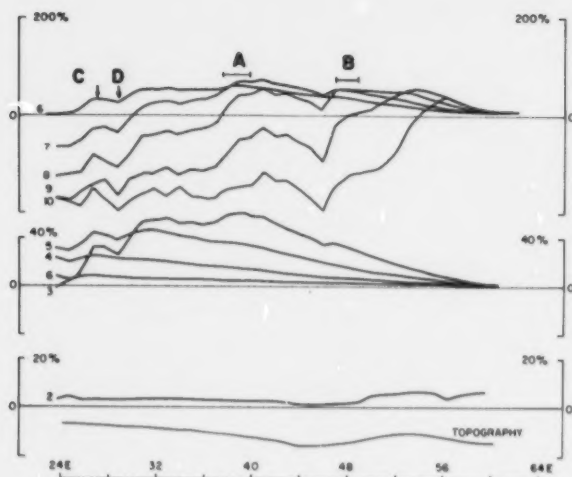


Figure 38.27. UTEM profile, Line 32N; H_2 CH-1 normalized; T_x to east; for the Red Dog Deposit, Alaska, USA.

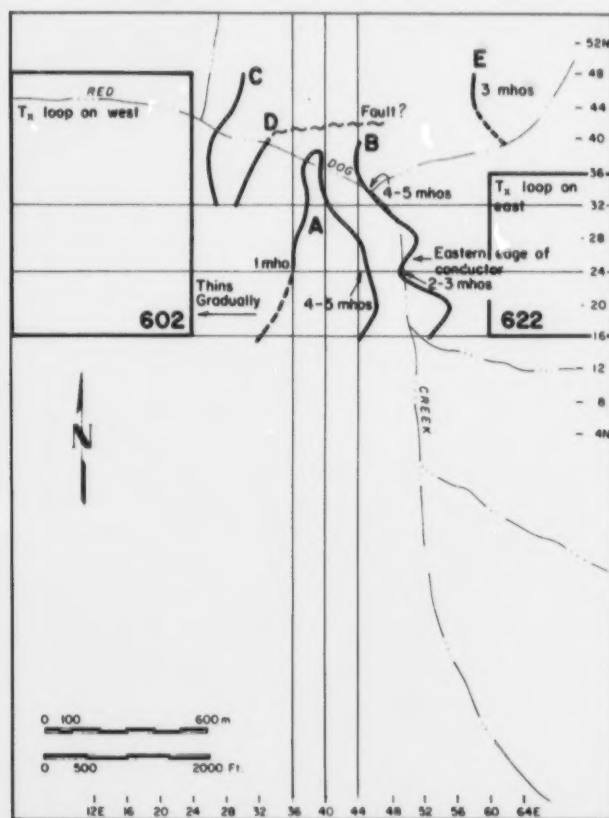


Figure 38.28. Interpretation map of the UTEM survey of the Red Dog Deposit, Alaska, USA (Eadie 1983).

found at 1 millisecond; this effect is probably due to multiple eddy current vortexes at late times.

Controlled Source Audio Frequency Magnetotellurics

The deposit was also surveyed using CS-AMT. We used CS-AMT because the technique is sensitive to flat-lying, weakly conductive zones and lateral inhomogeneities.

The frequencies ranged from 2048 Hz to 8 Hz in binary step (2048, 1024, 512 ... 8). The receiving dipole spacing was 400 feet; selected areas were surveyed with a dipole spacing of 200 feet. The source was a large loop 3 miles north of the deposit; selected areas were also resurveyed using a large dipole source 5 miles to the north. The orientation was selected to measure the electric field perpendicular to strike. The separation between the receiver and transmitter was not large and "near field effects" are present in some of the data which do not adversely affect it. The data were inverted using one- and two-dimensional techniques. The one-dimensional approach proved to be adequate. Our interpretation technique involves a preliminary, simple Bostic inversion producing one layer for each frequency (Bostic 1977). This model is then simplified and used in a one-dimensional inversion whose results are hand-stitched together to form an interpreted section.

The results are presented in pseudo section with apparent resistivities and phase shift; a separate section presents the interpretation. The contoured apparent resistivities at 512 Hz are also presented in map form to indicate the continuity of data from line to line.

LINE 16N (Figures 38.5, 38.29 and 38.30)

The raw data pseudo section can be compared to the grade section (see Figure 38.5). The apparent resistivities immediately focus one's attention to the low extending from station 36E to 52E which correlates with the mineralization. The phase data is used in the inversion and is presented here only for completeness. The other area which contains low resistivities is station 24E which is interpreted to be the response from a near vertical shear or fault.

In the inverted section (see Figure 38.30), the mineralization manifests itself in a complex zone with interpreted resistivities ranging from 6.5 to 152 ohm-metres. The edge of the mineralization is accurately depicted; however, the absolute depth is slightly overestimated.

LINE 24N (Figures 38.6, 38.31, and 38.32)

The pseudo section depicts the mineralization extending from station 36E to station 44E. The low resistivity at station 24E was originally interpreted as a vertical fault or shear and the subsequent drilling confirmed this to be fault related. The interpreted section agrees with the mineralization, but the interpreted depths seem to be overestimated. There are several untested conductors present.

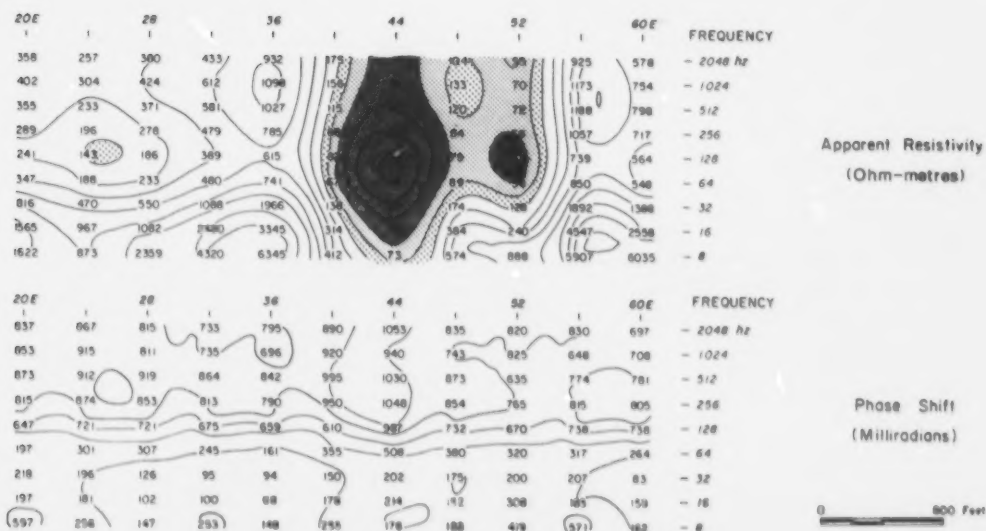


Figure 38.29. CS-AMT pseudo section, Line 16N, for the Red Dog Deposit, Alaska, USA.

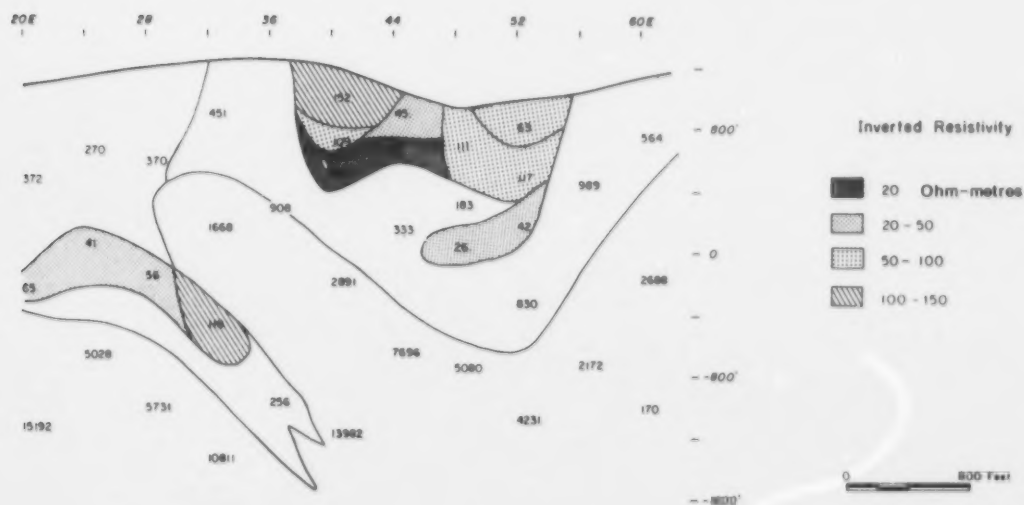


Figure 38.30. CS-AMT interpreted section, Line 16N, for the Red Dog Deposit, Alaska, USA.

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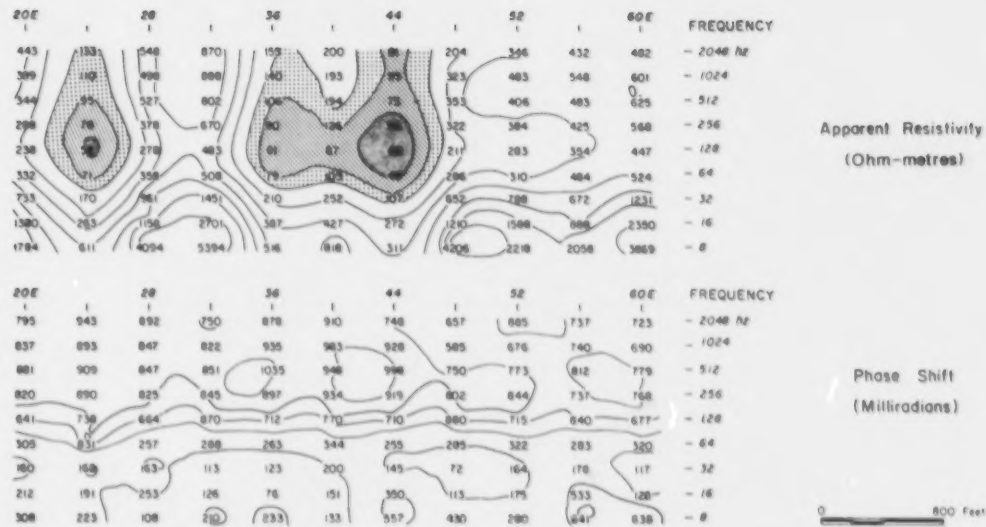


Figure 38.31. CS-AMT pseudo section, Line 24N, for the Red Dog Deposit, Alaska, USA.

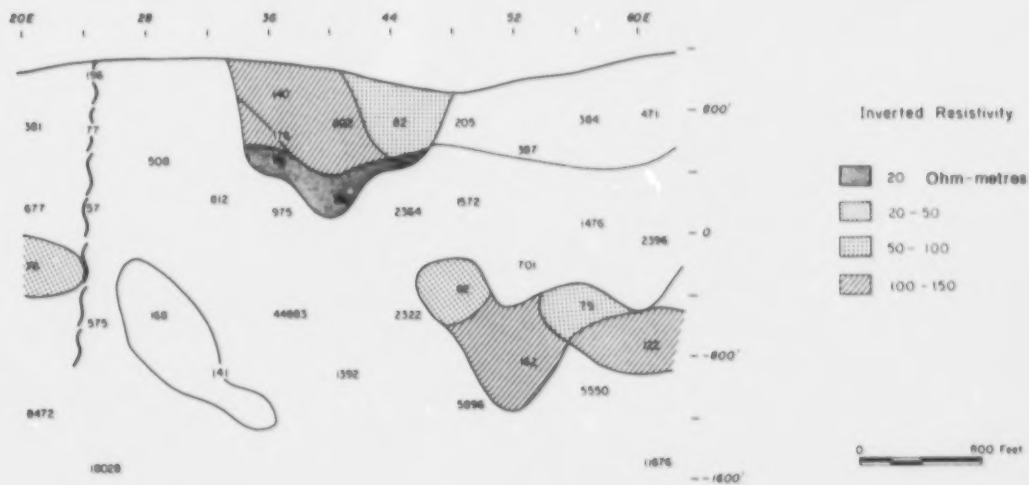


Figure 38.32. CS-AMT interpreted section, Line 24N, for the Red Dog Deposit, Alaska, USA.

LINE 32N (Figures 38.7, 38.33, and 38.34)

The raw data show the response to the mineralization which extends from station 32E to 40E. There is another indicated conductor near station 52E at depth. The zone at station 24E was correctly interpreted as a vertical shear or fault. The lowest interpreted resistivity corresponds to the highest metal content on the grade section. There is another interpreted low zone at stations 40E, 44E, and 48E which is untested.

Figure 38.35 shows the contoured apparent resistivity measured at 512 Hz; this can be compared to the combined foot-percent Zn+Pb (see Figure 38.4). The main deposit is within the contour which

is less than 150 ohm-metres and correlates well with the greater than 2500 foot-percent Zn+Pb. The Hill Top Deposit is also clearly defined by the contoured data.

Plates 38.1, 38.2, 38.3 (see Colour Folio near back of book) are coloured sections of line 32N for the raw apparent resistivities, the inverted CS-AMT, and the foot-percent Zn+Pb. All were processed in a similar fashion to minimize any effects due to computational bias. The two AMT sections correlate well with the grade section, reinforcing the usefulness of the AMT technique.

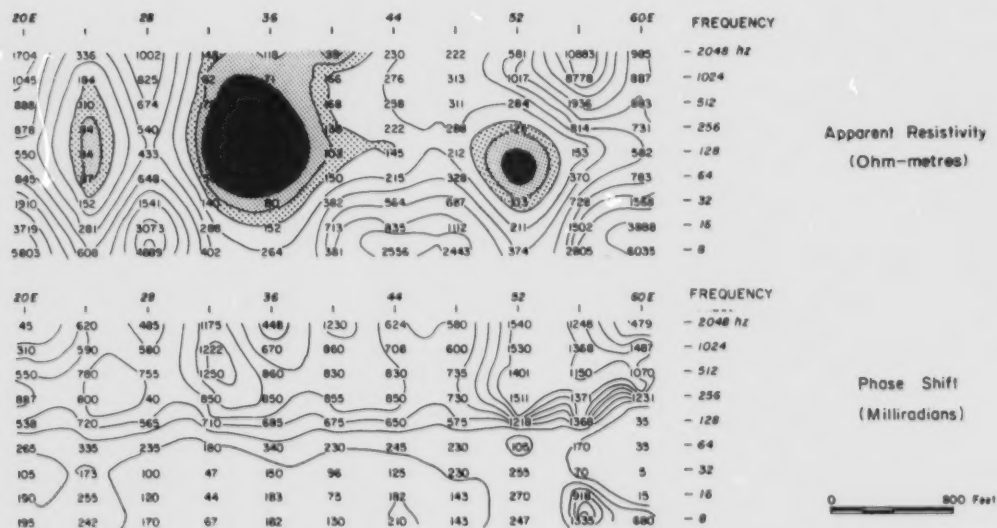


Figure 38.33. CS-AMT pseudo section, Line 32N, for the Red Dog Deposit, Alaska, USA.

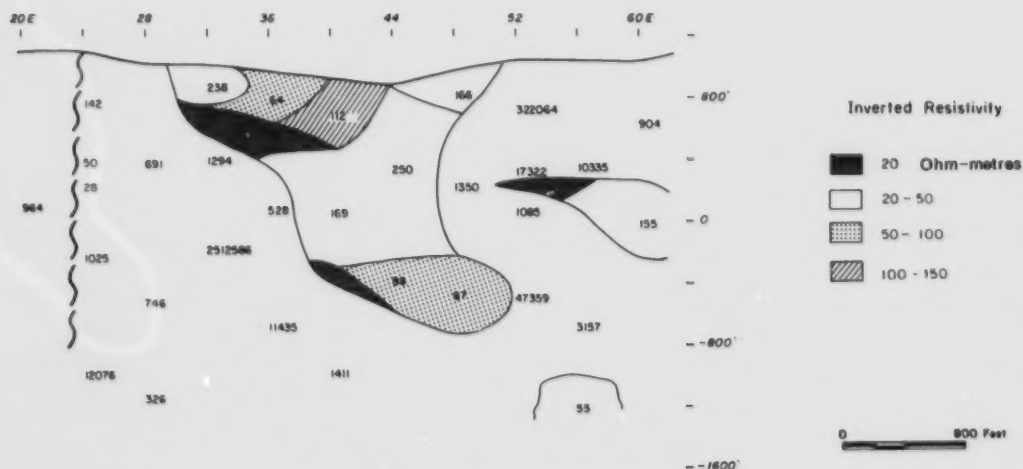


Figure 38.34. CS-AMT interpreted section, Line 32N, for the Red Dog Deposit, Alaska, USA.

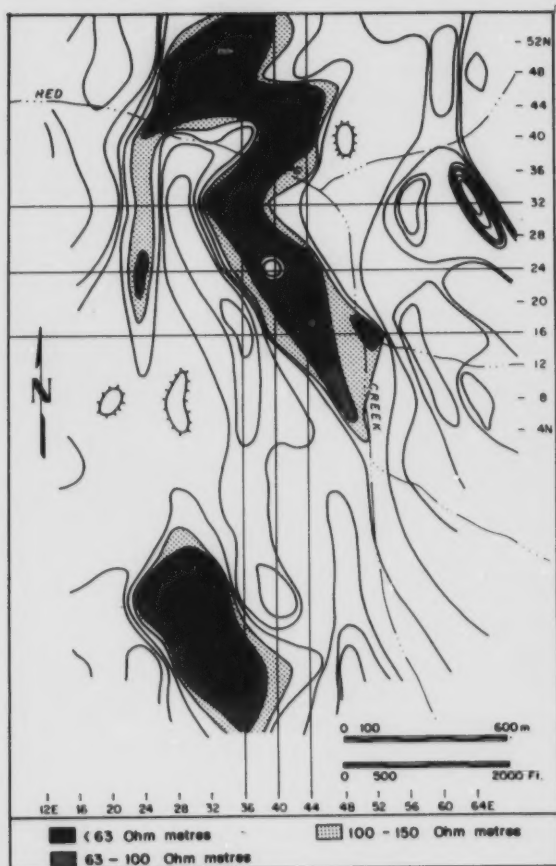


Figure 38.35. CS-AMT contoured ρ_h 512 Hz; 400' receiver dipole; for the Red Dog Deposit, Alaska, USA.

The results from this survey have clearly established that CS-AMT is an exceptional technique to be utilized in the exploration for these types of deposits, both for shallow occurrences and for deeply buried deposits.

SUMMARY

SUMMARY AND CONCLUSIONS

The complexity or simplicity of the deposit depends upon the scale that is being viewed. On a large scale, geophysical responses indicate a deposit consisting of a large localized zone of high sulphide rock nested in an envelope of semi-massive sulphide. However, detailed geophysical and geological data suggest that the deposit is much more complex. On detailed examination it consists of a number of independent conductive zones (probably sulphide chimneys) which are composed almost entirely of sulphides contained within an envelope of lesser amounts of sulphides (fine-grained sulphide exhalites). The

later zone was crystallized rapidly, generally is fine grained, and is not electrically interconnected over large areas.

The presence of organic carbon and pyrobitumen indicates that the deposit was never subject to high temperatures and pressures. Thus, heat and pressures were not available to metamorphose the organic carbon to graphite or to substantially recrystallize the conductive sulphides. This lack of intergrowth, along with the presence of silica, sphalerite, and nonconductive organic hydrocarbons, as well as the internal structure of the deposit consisting of several mineralized and unmineralized plates, tend to produce a deposit with only a moderately low resistivity.

The deposit as a whole is weakly to strongly polarizable, weakly to moderately conductive, and has a good resistivity contrast with the host rocks. Although there are abundant black shales, graphite is not common. Locally, the deposit manifests itself as a resistivity low in comparison with the silicified host rocks. On a broader scale, there are several conductors found in Cretaceous rock, the Kivalena Member, and in areas where saline waters have invaded gravels, muds, and rocks.

There is a good density contrast with the unmineralized country rock; however, the density contrast with rocks containing barite is poor. The magnetic response is low to nonexistent, because of an extremely low magnetic susceptibility. The deposit is easily discernable at shallow depth in its environment with almost any geophysical technique except magnetics. The detection of a similar deposit at depth becomes more difficult, and more selective techniques are necessary (such as CS-AMT) because of the deposit's low response parameters.

The response of the deposit points out the shortcomings of using a simple model to explain the response of a complex feature. Any one simple model falls short; however, a simple model gives one insight into understanding the complex feature. Where the simple model fails to match, valuable information can also be extracted about the complex feature.

The response parameters are summarized in Table 38.2. The data was compiled from surveys, *in situ* tests, core tests, and model studies. These values should be useful in evaluating data from surveys from similar deposits.

ACKNOWLEDGMENTS

We would like to gratefully acknowledge the efforts of others. First we would like to thank Cominco American Incorporated who allowed us to present this data. Geotrex Limited must be acknowledged for their airborne work, collecting the IP and some of the HLEM and gravity data, and Questor for their reflight on the area. John McBeth and Bob Hammond must also be recognized for their field work, as well as Bob Hennessey, our technician. The geo-

TABLE 38.2. SUMMARY OF PHYSICAL PROPERTIES.

		RESISTIVITY (ohm-metres)			
		1	10	100	1000
Mineralization	Core		X	XXXX	
	In situ		XXXXXXXXXXXX		
	CS-AMT "inverted"		XXXXXXXXXXXXXXXXXXXXXXXXXXXX		
Unmineralized					
	In situ "Kivalena and Cretaceous"		?XXXXXXXXXXXXXXXXXXXX		
		CHARGEABILITY (milliseconds)			
		1	10	100	1000
	In situ mineralized		XXXXXXXXXXXX		
		DENSITY (gm/cm ³)			
		2	3	4	5
	Core mineralized		XXXXXXXXXXXXXXXXXXXX		
	Model studies mineralization		XXX		
	Calculated Bouguer densities country rock		XXX		
		SUSCEPTIBILITY (k × 10 ⁻⁶)			
		1	10	100	1000
	Core		XXXX		
		CONDUCTIVITY-THICKNESS			
Method		1	10		100
	INPUT		X	X	X ?
	HLEM		XXXXXXXXXXXX		
	AMT		XXXXXXXXXXXXXXXXXXXX		
	UTEM		XXXXXXXXXXXXXXXXXXXX		

logical staff, Joe Plahuta, Dave Moore, Janet Modene, Lorne Young, John Robertson, Roy McMichael, and Jerry Booth, for their efforts and assistance are also acknowledged, as is Lorne Young for his review of the geological section.

The UTEM was run and interpreted by Tom Eadie, Cominco Limited, and his effort is truly appreciated. The gravity contribution by David Barnes of the U.S. Geological Survey is also appreciated. The painstaking effort of George Koehler for his critical review and suggestions and the encouragement by George Tikkanen, who first suggested the paper, are appreciated. The drafting by our staff and specifically Steve McGlocklin was essential to the paper. Lastly, the painstaking effort of our secretaries, Karen Dunham and Carol Goodsole, is gratefully acknowledged. There are many other present and past employees of Cominco American whose efforts helped make this possible, as well as members of contract crews; all are thanked and acknowledged.

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39. Electromagnetic Exploration for Sulphides in Australia

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ABSTRACT

The ancient land surface of much of Australia is arid and deeply weathered. This leads to special problems in the application of geophysical methods to mineral exploration. The deeply weathered overburden, usually porous and permeated with saline groundwater, often forms a barrier for electrical and electromagnetic methods. The weathering process also forms maghemite, a magnetic iron oxide which can obscure the magnetic response from deeper targets or cause spurious anomalies.

These same characteristics can sometimes be used to advantage in exploration and some innovative approaches have been devised.

This paper illustrates, with examples of field data, both the problems and advantages of exploring in weathered terrains. All the field examples are from Australia, not all are successful case histories but even the unsuccessful examples have a message.

INTRODUCTION

The ancient, arid land surface over much of Australia is characterized by depths of oxidation and weathering of up to 100 m. Alluvium in the form of transported silts, clays, and saline evaporite deposits is found in paleodrainage systems. Laterite profiles have been developed over both alluvium and oxidized bedrock. Clays and saline groundwater give electrical resistivities in the range 0.3 to 100 Ω -m (ohm-metres); overburden conductances in the range 0 to 100 S (siemens).

In some cases, weathering (hydration) of magnetite produces a nonmagnetic species of iron oxide in the weathered zone. In other cases the magnetic character is preserved. During the process of lateritization, a magnetic species of iron oxide, maghemite, is developed in the pisolite zone. Maghemite typically displays variable remanence, susceptibility, and superparamagnetic (SPM) behaviour. Pisolites may be concentrated by fluvial processes in buried paleo-channels. These features are illustrated in cartoon form in Figure 39.1.

Weathering and peneplanation result in a usually gentle topography; together with an arid climate, this results in ideal conditions for low flying and hence widespread use of airborne methods—particularly magnetics and radiometrics.

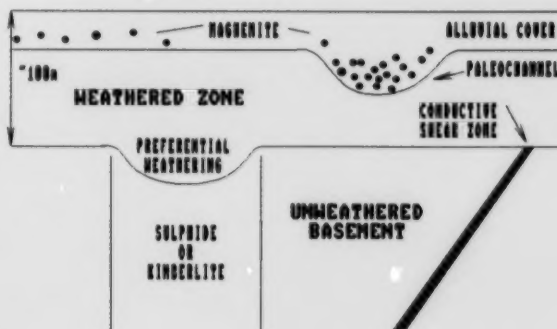


Figure 39.1. Geophysical characteristics of a typical section in weathered terrain.

Deep weathering and conductive surface material make the application of traditional electrical and electromagnetic techniques difficult and often ineffective. The development and extensive use of transient electromagnetic (EM) methods both on the surface and in drillholes has overcome these difficulties in many cases, but in turn it has created some new problems.

Exploration in weathered terrains is usually considered more difficult than it would be, for example, within the Canadian Shield. Some of the negative features of exploration in weathered terrains are listed in Table 39.1. These same terrains, however, offer some advantages and some of these positive features are listed in Table 39.2.

While extensive use is made of airborne magnetic and airborne radiometric techniques in exploration over weathered terrains, this paper will concentrate on airborne ground and drillhole electromagnetic methods. Four case histories of exploration projects are considered: Freddie Well, Broken Hill, Flying Doctor, and Woodchester.

TABLE 39.1. NEGATIVE FEATURES OF WEATHERED TERRAINS.

- | |
|--------------------------------------|
| 1. Thick and variably oxidized cover |
| 2. Conductive surface layer |
| 3. Saline groundwater |
| 4. Development of maghemite |

TABLE 39.2. POSITIVE FEATURES OF WEATHERED TERRAINS.

1. Relatively gentle topography
2. Arid climate
3. Differential weathering
4. Development of maghemite

AIRBORNE ELECTROMAGNETIC METHODS

In general, the airborne electromagnetic method (AEM) has not been widely used in Australia and it has not been as successful in weathered terrains as it has been in Canada. Deep and variable weathering tends to mask basement conductors and produce spurious anomalies in the weathered layer. The extreme conditions which cause these problems are not ubiquitous, however, and Geotrex have been operating INPUT®, a fixed wing transient system (e.g. Lazenby 1973), in Australia since the early 1970s. DIGHEM, a bird mounted frequency domain system (see for instance, Fraser 1979), has also operated in Australia with some success, chiefly in the less deeply weathered parts of the continent.

Geotrex has made a number of technical changes to their INPUT systems since the early 70s, mainly prompted by the requirements of weathered terrains in Africa and Australia (G. Butt, personal communication, 1985). These include:

1. increased transmitter power for improved signal at late times
2. increase from six to twelve channels with some earlier delay times to improve layered inversion results
3. digital-data acquisition to permit routine interpretative processing
4. shorter integration time giving better anomaly resolution and amplitudes, and rise times which more closely match theoretical models

Freddie Well

The Freddie Well Deposit (Butt 1985), a small copper-zinc massive sulphide body, is reasonably typical of the traditional airborne EM target. It occurs in the arid, deeply weathered, Archean shield of Western Australia, where AEM has not generally been very successful.

Figures 39.2 and 39.3 show Geotrex INPUT data collected in 1975 and 1984, respectively. The flight lines were approximately coincident and close to the geological section shown in Figure 39.4.

The large-amplitude broad response which dominates both profiles is due to conductive sediments. The smaller, adjacent anomaly with a slower

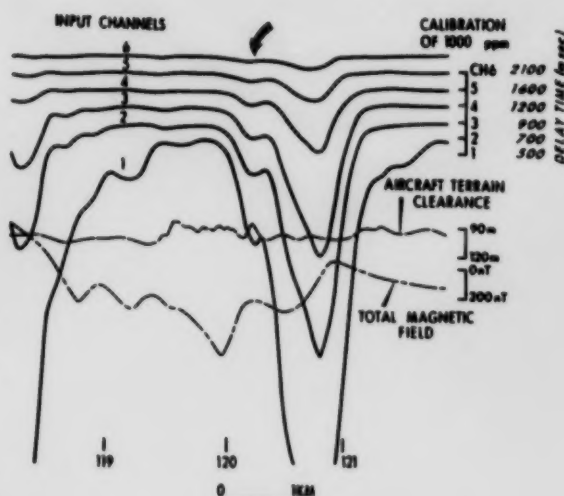


Figure 39.2. Freddie Well Deposit, W.A., geophysical data profile, line 19 (1975) (courtesy of Geotrex Pty. Ltd.).

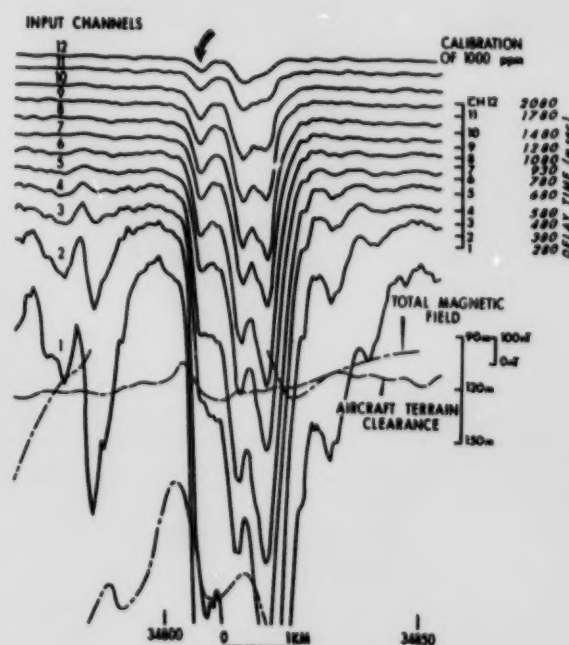


Figure 39.3. Freddie Well Deposit, W.A., geophysical data profile, line 208.1 (1984) (courtesy of Geotrex Pty. Ltd.).

decay rate corresponds with the more conductive Freddie Well massive sulphides.

The 1984 data were recorded with an improved receiver using a shorter integration time and recording twelve channels compared with six in 1975. The

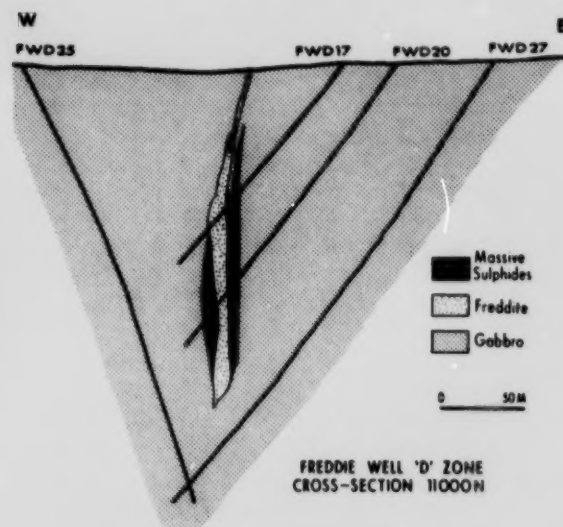


Figure 39.4. Freddie Well "D" Zone, cross-section 11 000N (courtesy of Geotrex Pty. Ltd.).

shorter integration time results in the field data more closely matching theoretical rise times and amplitudes for a narrow conductor. With better anomaly resolution and additional channels, more quantitative interpretation is possible.

GROUND ELECTROMAGNETIC METHODS

Time domain electromagnetic (TEM) systems have dominated ground electromagnetic (EM) survey activity in Australia for both mineral exploration, including conductor detection and geological mapping, and depth sounding, since the introduction of the SIROTEM MkI in 1977. The main systems in use today are the SIROTEM, EM37, UTEM, ZONGE GDP 12, NEWMONT EMP, and CRONE PEM. Figure 39.5 shows the survey configurations in common use.

Coincident loop, offset loop, and inloop modes tend to be widely used in the reconnaissance mode, whilst the Turam geometry is employed for detailed investigations, particularly where significant depth of penetration is required. However, other parameters such as target geometry and conductivity, overburden properties, and relief and vegetation in the survey area are also relevant. Slingram, offset loop, in-loop, and coincident loop geometries are often preferred for reconnaissance surveys, because the transmitter and receiver are moved together, illuminating the target from different directions. Furthermore, each reading can be directly compared without concern for the transmitter "overprint", caused by conditions local to the transmitter and the asymmetries invariably introduced by fixed transmitter systems. Semiarid terrain with typically sparse vegetation is ideal for coincident loop type surveys. Under such

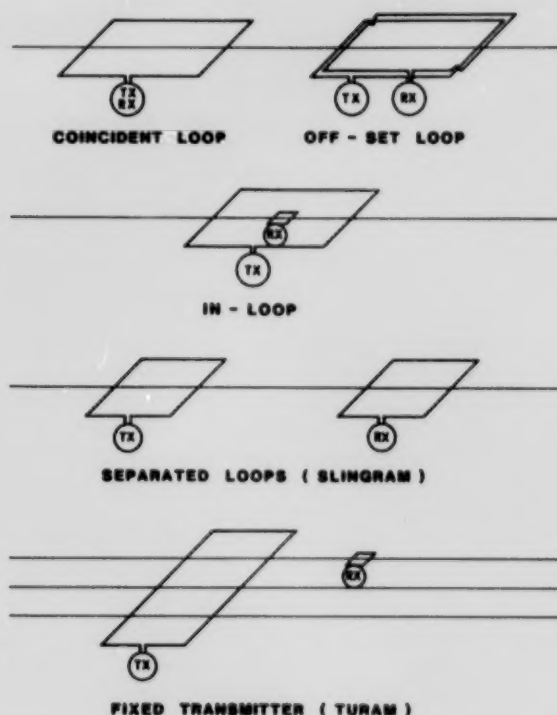


Figure 39.5. Ground EM survey configurations.

conditions, coincident-loop surveys using a 200 m loop with 200 m moves (i.e. continuous coverage) can be carried out for about twice the cost of an airborne INPUT survey.

Some advantages of the Turam geometry, in addition to the greater depth of penetration resulting from the larger transmitter loop, include the detection of poorer and deeper conductors through the channelling of currents flowing within the host rock; the extra definition of conductors available from the measurements of more than one field component; and, finally, the relative ease with which measurements can be made in heavily wooded terrain.

Transmitter loop sizes in the range 600 by 300 m to 1200 by 600 m are normally utilized in the Turam mode. In reconnaissance work, the vertical field is measured through and on both sides of the loop, whilst for detailed surveys the loop is positioned to maximize coupling to the conductor. The three components of the induced magnetic field are often measured in this mode. The Commonwealth Scientific and Industrial Research Organization (CSIRO), with financial support and direction from mining companies through collaborative projects coordinated by the Australian Mineral Research Association (AMIRA), has developed interpretation aids for TEM-survey modes commonly employed in Australia using computer and scale modelling. A wide range of software for the forward and inverse

modelling of TEM data over one-, two-, and three-dimensional earths is available to sponsors. Parametric studies using both numerical and scale models are also available.

The choice of loop system in a particular situation is governed by two factors, in addition to those mentioned above. Firstly, the asymmetries associated with TURAM surveys can give apparent spurious anomalies at the edge of a horizontal conductor—typically either an alluvial cover or a change in weathering. This asymmetry can be a significant problem with the fixed loop TEM. Consequently, most reconnaissance surveys tend to use one of the coincident loop configurations.

Secondly, offset loop and inloop modes rather than coincident loops are utilized to reduce the effect of super paramagnetic (SPM) material in weathered or transported overburden. Buselli (1982) demonstrated that SPM material generates a signal that decays as the inverse power of time (t^{-1}). Electromagnetic induction generates a t^{-1} decay only at the inductive limit (very early times); at later times the decay is much faster. As a result SPM effects can dominate the response at late times. Both the elevated response at late time and the slow rate of decay produced by SPM effects suggest a deep, good conductor. Where the layer of material containing SPM iron oxides is relatively shallow, the effects are only significant, relative to EM induction, close to the transmitter wire (Lee, personal communication, 1987).

Offsetting the transmit and receive loops by 1 to 3 m is often sufficient to remove these effects. Alternatively, the field can be measured at the centre of the loop with a coil of suitable sensitivity. SPM iron oxides are sufficiently widespread throughout the weathered Australian continent to dictate the use of offset or inloop configurations in the majority of surveys where coincident loop geometry is required (R.P. Timmins, personal communication, 1987).

Broken Hill

Frequently, TEM measurements with coincident loop configuration give negative responses which cannot be readily explained by conventional EM theory. These negatives have caused a great deal of debate and they have been variously ascribed to instrument problems, operator error and so forth by the unbelievers. The evidence is now overwhelming that many of these negatives are real and, in many

cases, can be confidently interpreted as induced polarization effects.

Figure 39.6 (after Flis *et al.*, in press) shows an example of early time SIROTEM measurements in the Broken Hill district in the state of New South Wales. These measurements were made with 100 m square loops, displaced by 15 m. The reading interval was 25 m. Although the early channels give a conventional positive response, the effect becomes negative after a delay of about 0.6 ms. This type of response is quite common. Figure 39.7 shows scale-model results for a wide, near-surface, nonpolarizable conductor (Buselli 1985). The response is positive, as one would expect. Figure 39.8, after G. Hohmann (personal communication, 1987) shows computer modelling of the response over a similarly shaped, polarizable body with Cole-Cole parameters as shown. Note that a chargeability of only 0.1 was sufficient to give a pronounced negative response. Extensive studies by several workers (Raiche *et al.* 1985; Flis *et al.*, in press) have shown a complex relationship between the Cole-Cole parameters and TEM response. The geo-electrical section which gives the most pronounced negative TEM response may not necessarily give a pronounced IP response, as a consequence of the different modes of measurement.

Figure 39.9 show the results of a dipole-dipole time domain IP survey on the same line. There is a significant surficial low-resistivity zone between 2500 E and 3100 E but only a weak coincident chargeability anomaly.

The TEM data from station 2875 E is compared with model data for a polarizable layer over a half space ($R_0 = 9 \text{ ohmM}$, $M = 0.13$, $T = 0.001\text{S}$ and $C = 0.3$) in Figure 39.10. Although the match is not perfect it does fit well over most of the time range.

Detailed IP measurements were made with 2 m dipoles in the centre of the negative TEM zone. The IP decay curve was inverted to fit a Cole-Cole model and the parameters obtained were as follows: $R_0 = 9 \text{ ohmM}$, $M = 0.09$, $T = 0.0003\text{S}$ and $C = 0.25$. These are in reasonable agreement with the Cole-Cole parameters used in the TEM model.

It is apparently necessary to know the four Cole-Cole parameters for a complete interpretation—apparent resistivity and apparent chargeability are not sufficient to adequately explain a negative TEM response.

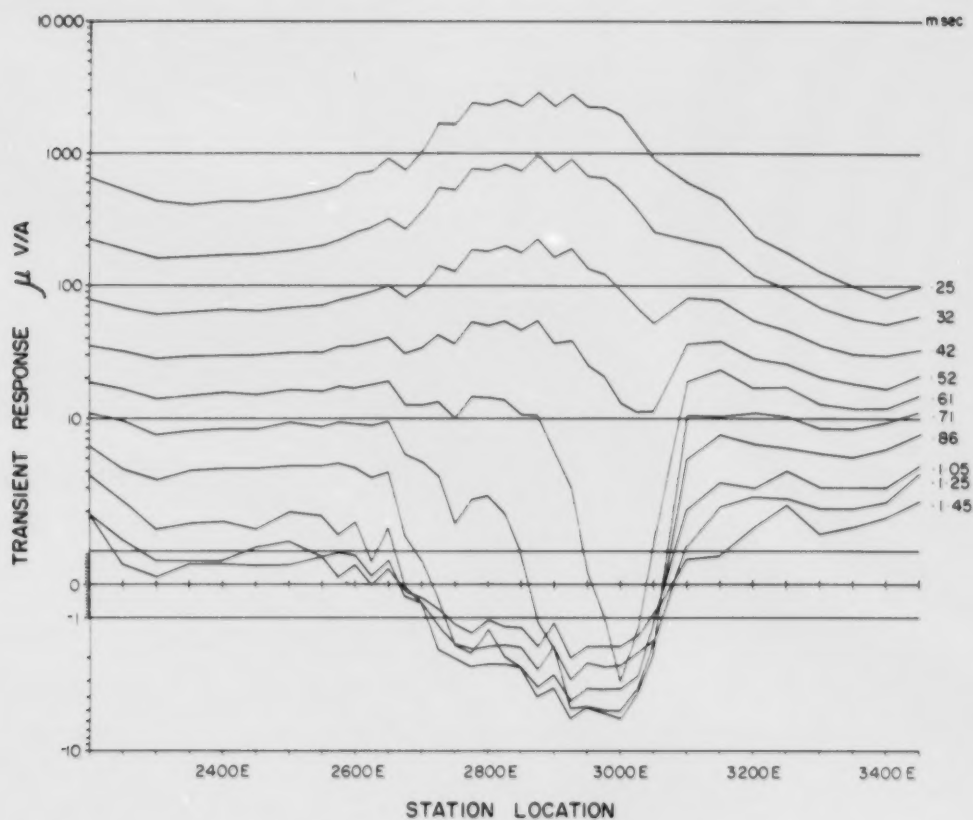
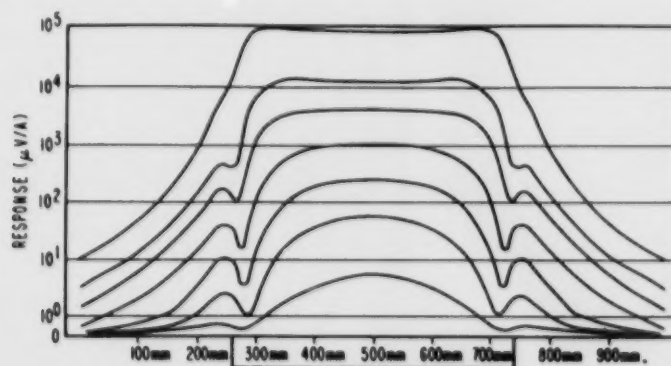


Figure 39.6. Early time SIROTEM profile, Broken Hill, N.S.W., 100 m square loops displaced by 15 m (M.F. Flis, personal communication, 1986).



MODEL PARAMETERS:

WIDTH: 486mm
STRIKE LENGTH: 399mm
THICKNESS: 50mm
CONDUCTIVITY: $4.9E+05$ S/m
SCALING FACTOR: 2000
COINCIDENT LOOP SIZE: 50mm

Figure 39.7. Scale model SIROTEM profile for a wide, near-surface, nonpolarizable conductor (after Buselli 1985).

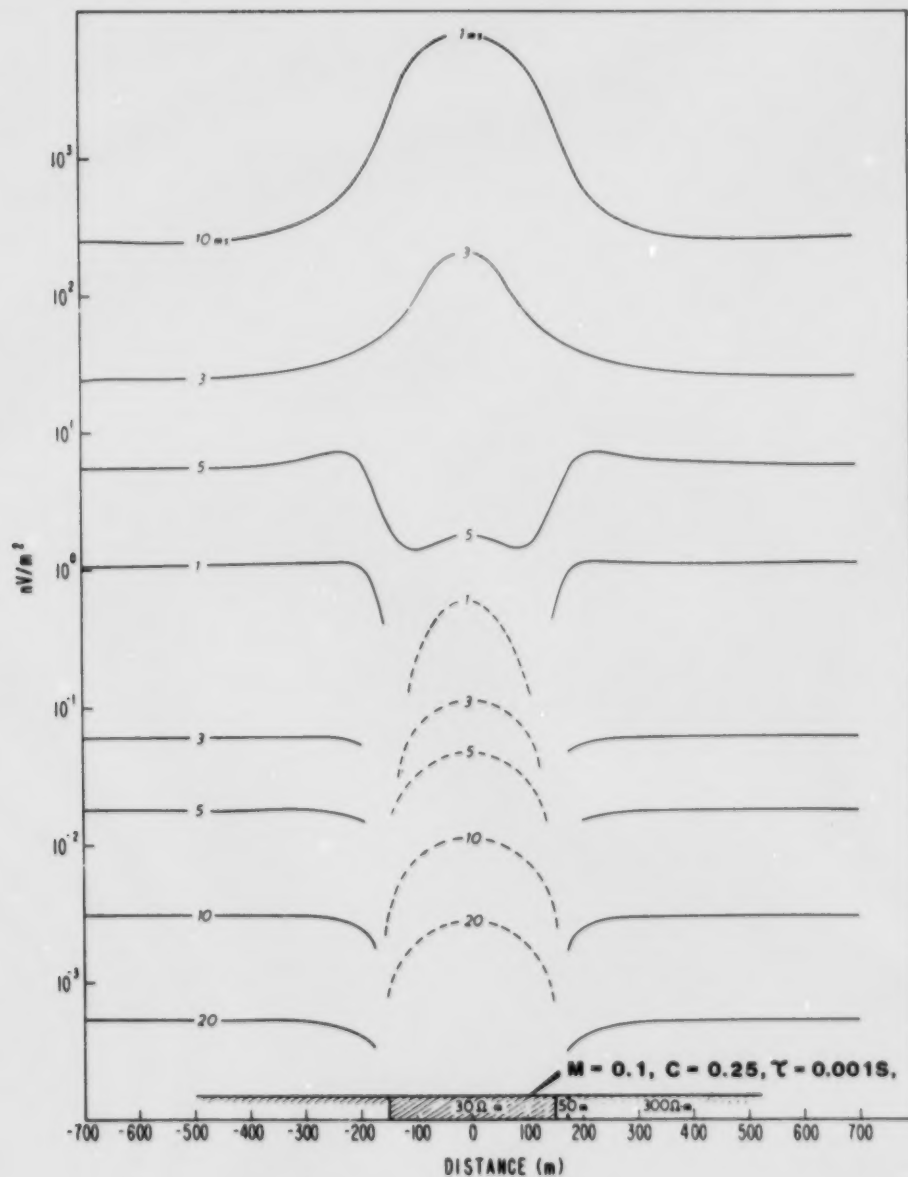


Figure 39.8. Numerical modelling of TEM response over a wide, near-surface, polarizable (chargeable) conductor (after G.W. Hohmann, personal communication, 1987).

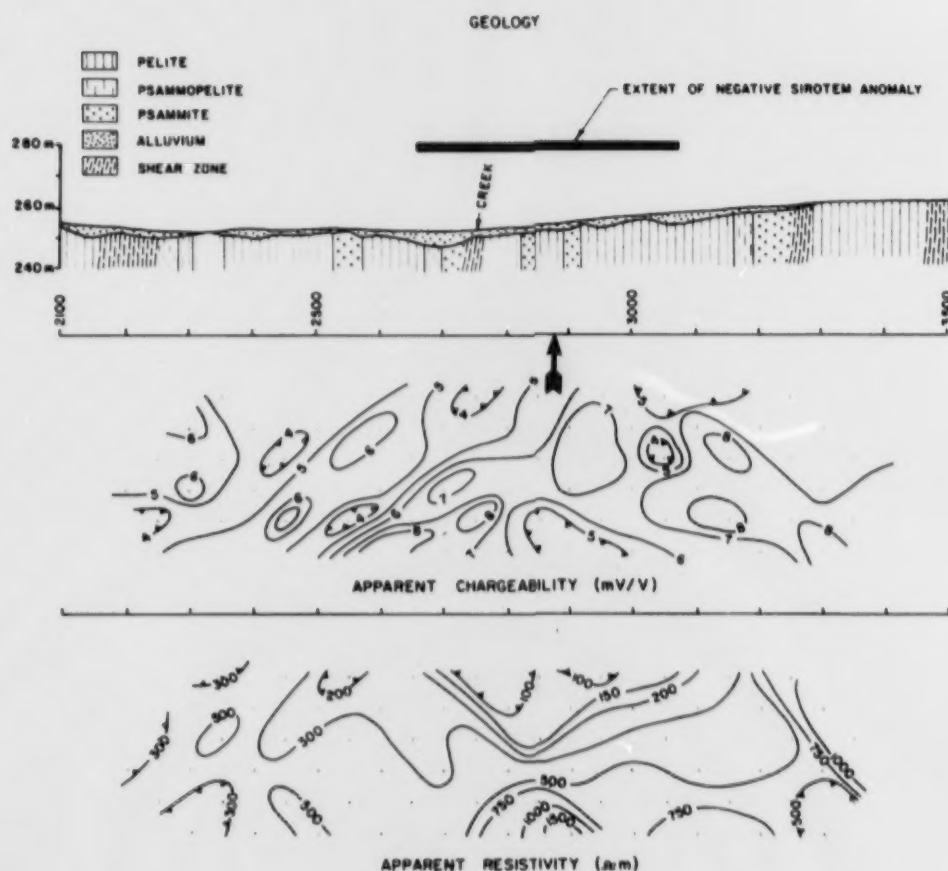


Figure 39.9. Dipole-dipole IP pseudo section over the profile shown in Figure 39.6, Broken Hill, N.S.W. (M.F. Flis, personal communication, 1986).

BOREHOLE ELECTROMAGNETIC METHODS

Surveying around a borehole most commonly uses transient electromagnetic (TEM) methods. With a large transmitter loop on the surface and the receiver downhole, the masking effects of the conductive surface layer can be minimized. Particularly, when several drillholes are available, the position of an "off hole" conductor can often be determined in space and additional drillholes sited to test it. Several groups now have filament inversion programs, initially developed by Newmont Pty. Ltd. (Barnett 1984), which permit the automatic determination of current filaments in space and hence conductor location.

Flying Doctor

The Flying Doctor Deposit near Broken Hill, New South Wales is a small (approximately 200 000 tonnes) deposit of lead and zinc sulphides which has been a popular test site for various methods. Newmont Pty. Ltd. conducted EMP surveys in four drillholes during August of 1981 (Boyd and Wiles 1984) and used inversion techniques to locate the optimum rectangular current loop which matched the field data.

Although Broken Hill is an arid area, often subjected to deep weathering, conditions at the Flying Doctor Deposit were not particularly severe. The depth of weathering was estimated at being 50 m.

Figure 39.11 illustrates the geological section, four drillholes investigated and the position of the transmitter loop. Figures 39.12, 39.13, 39.14, and 39.15 show EMP results in drillholes 3055, 3039, 3040, and 3071, respectively. Only drillhole 3040 intersected the conductor whereas drillholes 3055 and 3039 appear to have intersected mineralization in the weathered zone while 3071 passed about 25 m below the conductor. Some results obtained for drillholes 3055 and 3041 were affected by the steel casing and these have been deleted.

The host rocks at Broken Hill are quite resistive and the half-space response is not significant when compared with the response due to mineralization. Computer inversion gave the best fit current loop as shown in Figure 39.11. A comparison of field and model data for 2.08 ms delay is shown in Figure 39.16.

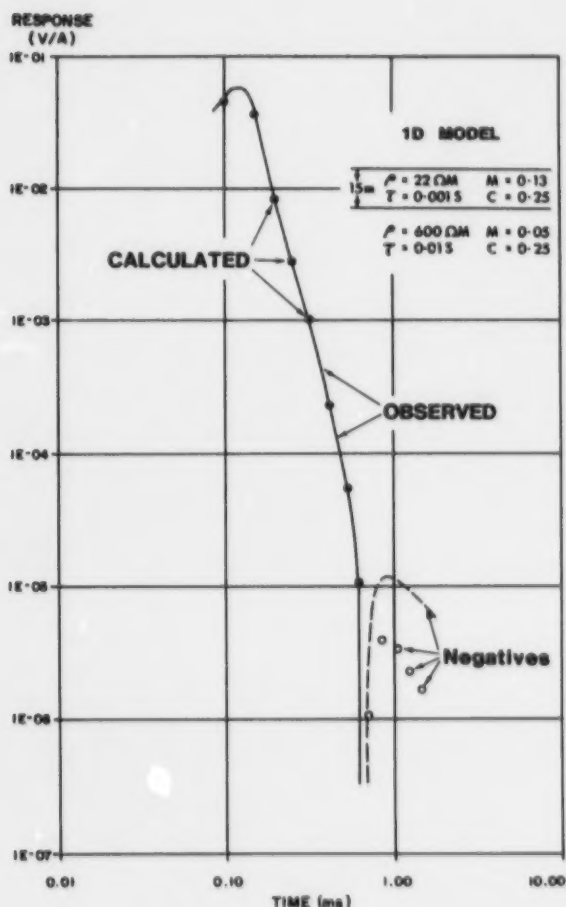


Figure 39.10. Observed TEM decay, station 2875, Broken Hill, N.S.W., versus calculated decay for a polarizable layer on a half space (M.F. Flis, personal communication, 1986).

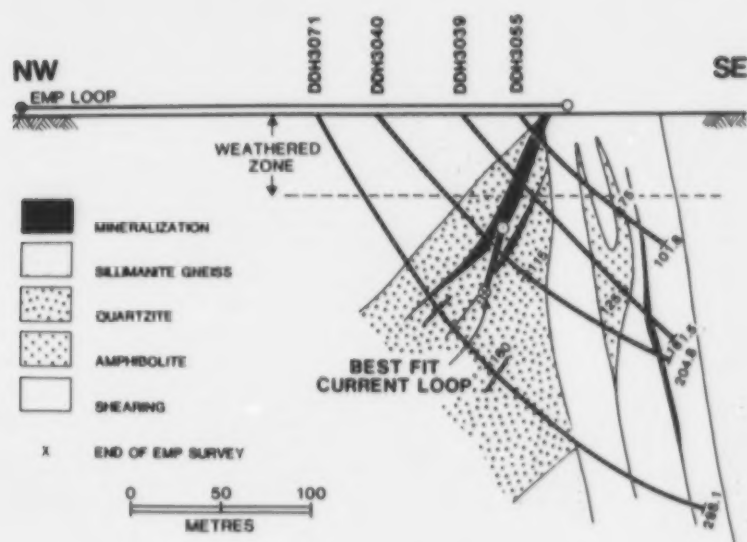


Figure 39.11. Geological section through DDH3071, DDH3040, DDH3039, and DDH3055, Flying Doctor Deposit, N.S.W. (after Boyd and Wiles 1985).

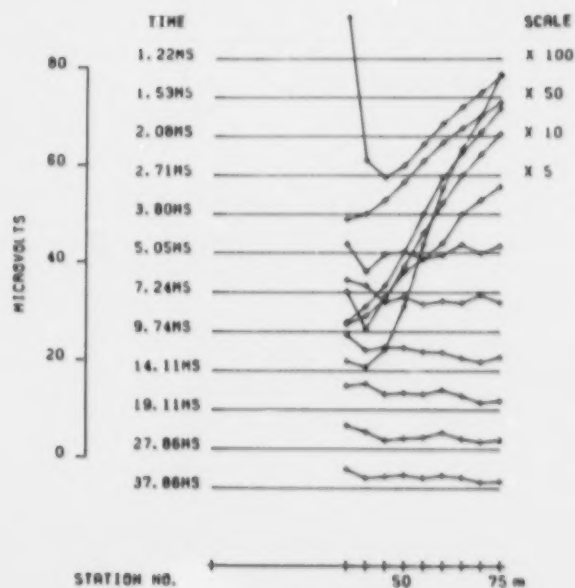


Figure 39.12. EMP results, DDH3055, Flying Doctor Deposit, N.S.W. (after Boyd and Wiles 1985).

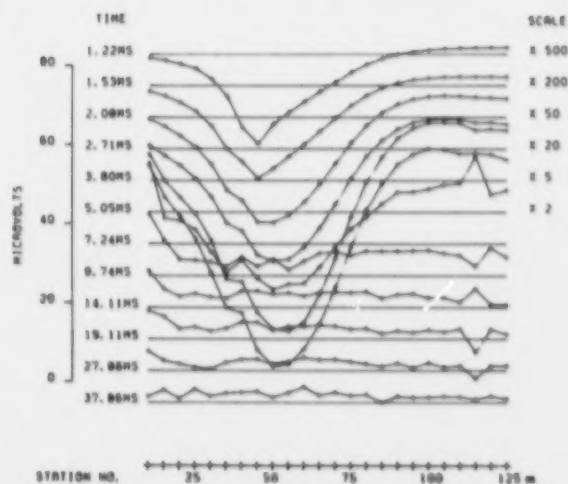


Figure 39.13. EMP results, DDH3039, Flying Doctor Deposit, N.S.W. (after Boyd and Wiles 1985).

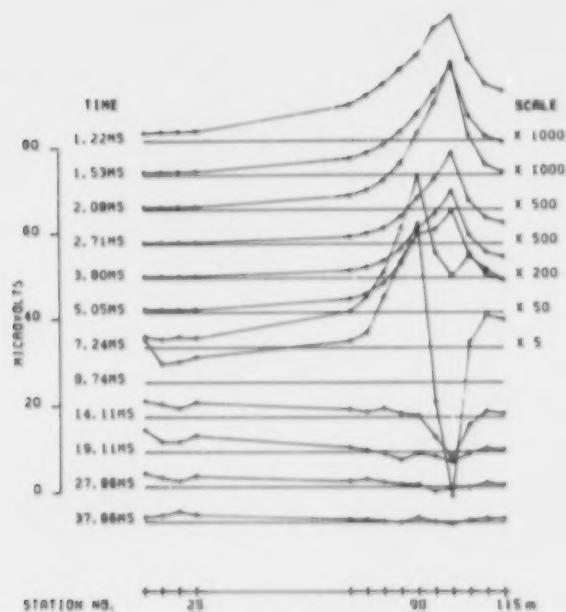


Figure 39.14. EMP results, DDH3040, Flying Doctor Deposit, N.S.W. (after Boyd and Wiles 1985).

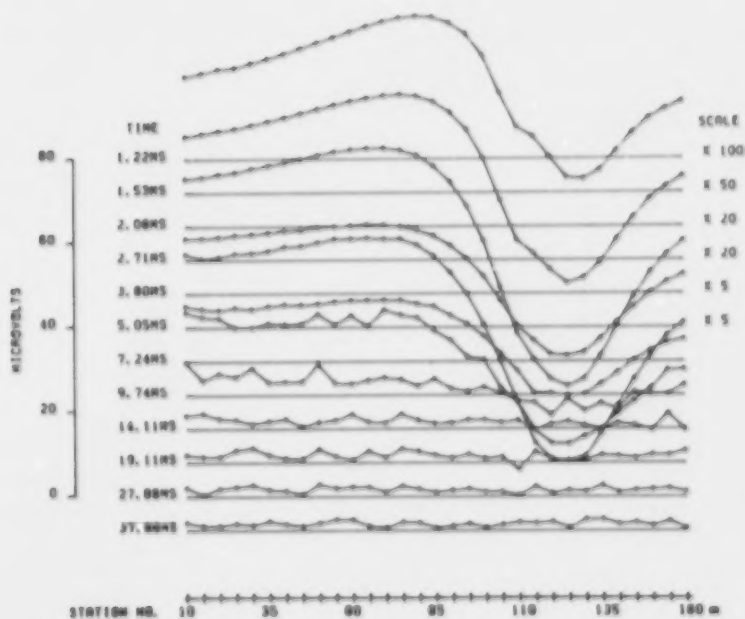


Figure 39.15. EMP results, DDH3071, Flying Doctor Deposit, N.S.W. (after Boyd and Wiles 1985).

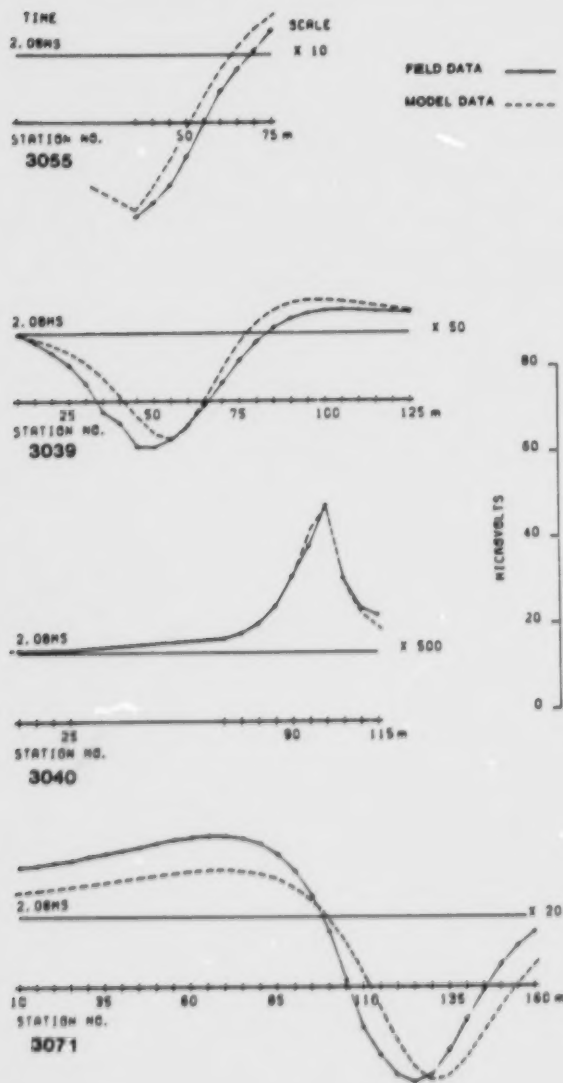


Figure 39.16. Comparison of EMP field and model data for a time delay of 2.08 ms, Flying Doctor Deposit, N.S.W. (after Boyd and Wiles 1985).

Woodchester

Most TEM systems currently in use in Australia (SIROTEM, EM37, Crone PEM, Newmont EMP) record the impulse response through the measuring of dB/dt . The combination of measuring dB/dt with a relatively conductive surface material (due to weathering) can lead to some unusual responses.

A recent case history from Woodchester in South Australia illustrates the effect of measuring dB/dt in a weakly conductive area (Lane 1987). Figure 39.17 shows surface SIROTEM profiles over a conductor interpreted as dipping to the west. Three percussion holes—WCP1, WCP2, and WCP3—were drilled to test it and all three intersected massive pyrite and pyrrhotite with only minor base-metal contents.

Hole WCP2 (Figure 39.18) intersected two intervals of massive pyrite and pyrrhotite. The anomalous magnetic susceptibility and conductivity measured by geophysical logs are shown in Figure 39.19. Figure 39.18 also shows two different transmitter loop positions used to survey WCP2 with downhole SIROTEM. The results are shown in Figures 39.20 and 39.21.

The channel one response reflects both host rock and discrete conductor effects. The long wavelength responses in channel 1 for both loop 1 and loop 2 are different, and are interpreted to reflect the 'smoke rings' within the host rock. The geometric shape of the 'host response' is shown in Figure 39.22. Note that the currents within the resistive host rock decay very quickly as indicated by the dif-

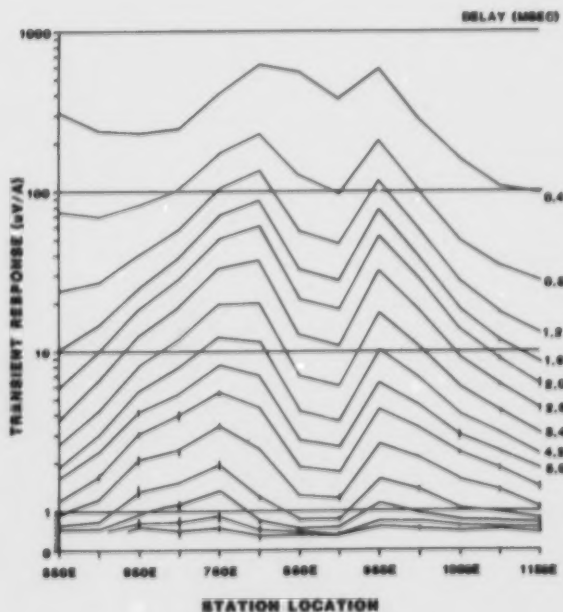


Figure 39.17. Coincident loop SIROTEM profile, Line 600N, Woodchester, S.A. (after Lane 1987).

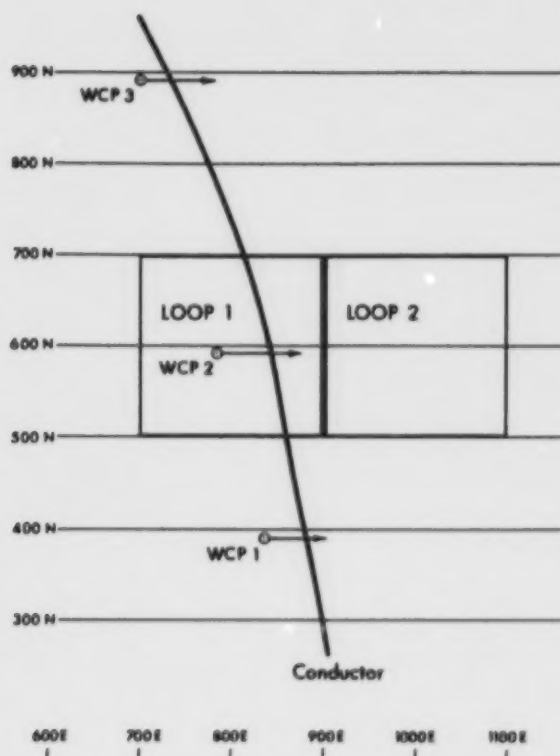


Figure 39.18. Survey grid and drillhole locations, Woodchester, S.A. (after Lane 1987).

ference between the long wavelength responses in channel 1 and subsequent delay times for each loop.

In addition to the host response which is superimposed on the conductor response in channel one, the sense of the conductor response in channel one is the opposite to that observed in later channels. This is attributed to the fact that the current density in the conductor is increasing at early times before decaying to zero, with a corresponding change in the sign of dB/dt .

CONCLUSIONS

Weathered terrains present new challenges to the application of geophysics in mineral exploration. They usually increase the depth to the target and often generate shallow, spurious anomalies. Geophysicists have met these challenges by the application of appropriate technologies which have in common the collection of larger volumes of data.

Gentle topography is common in arid climates resulting in the widespread use of relatively inexpensive airborne techniques—particularly magnetics and radiometrics—specifically directed towards geological mapping. Weathering can also be used to an advantage, such as in the mapping of lithotypes character-

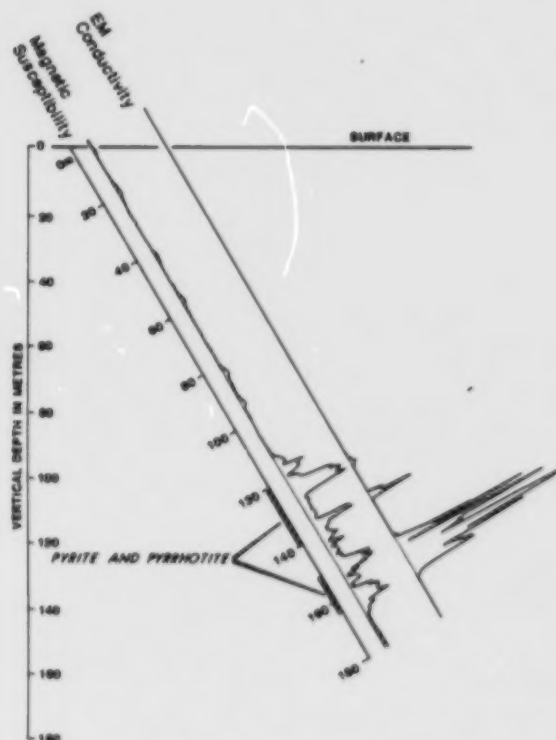


Figure 39.19. Magnetic susceptibility and EM conductivity logs, drillhole WCP2, Woodchester, S.A. (after Lane 1987).

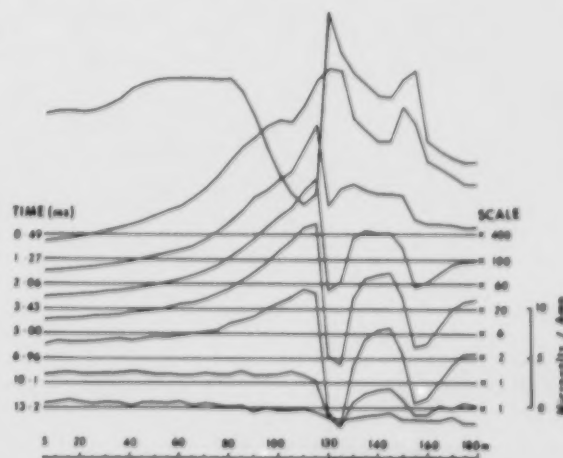


Figure 39.20. Downhole SIROTEM profile, WCP2 (LOOP 1), Woodchester, S.A. (after Lane 1987).

ized by different weathering profiles and in the detection of paleochannels through concentrations of magnetic pisolites. The examples considered above show that, with proper consideration, surface and

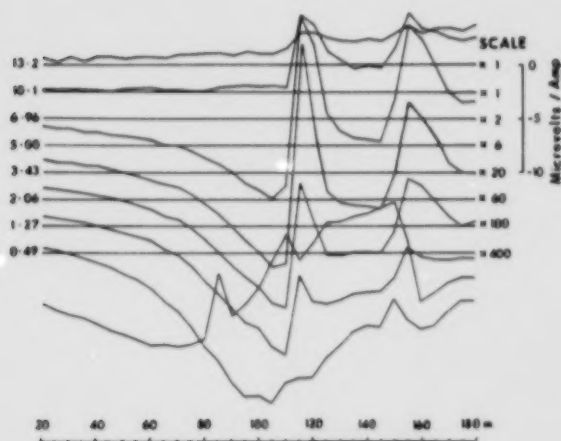


Figure 39.21. Downhole SIROTEM profile, WCP2 (LOOP 2), Woodchester, S.A. (after Lane 1987).

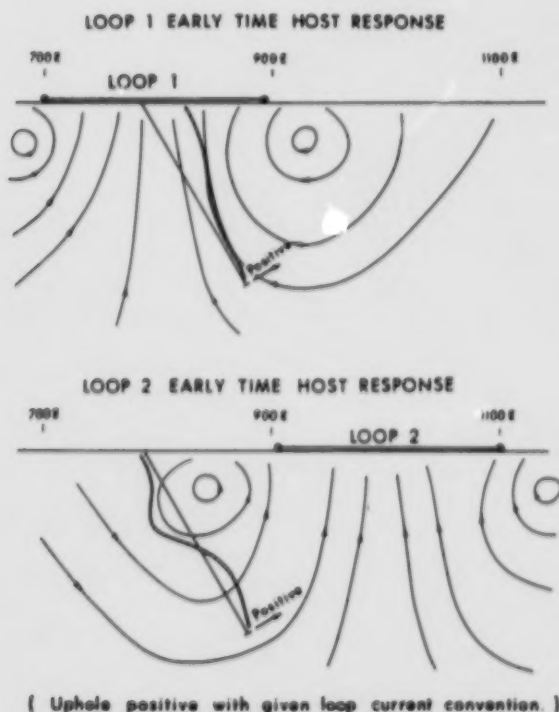


Figure 39.22. Diagrammatic representation of downhole TEM response, WCP2, Woodchester, S.A. (after Lane 1987).

subsurface electromagnetic methods can be successfully applied to exploration.

With a positive approach, many of the problems of exploration in weathered terrains can be turned into advantages, giving access to many large and

relatively unexplored areas of the earth's surface with considerable potential existing for discoveries.

ACKNOWLEDGMENTS

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40. Geophysical Response of Some Canadian Massive Sulphide Deposits

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ABSTRACT

Experience has shown us that the keys to successful massive sulphide exploration, particularly in areas of search below 400 feet subsurface, demand a highly integrated exploration approach. As Davidson and Coope (1979) earlier stated, "Certainly the geophysicist and the geochemist can sense many aspects of a geological environment that the geologist cannot observe. However, the conversion of geophysical and geochemical data into geological information is usually ambiguous and imprecise without the input of the geologist. Thus the objective of integrated exploration is to convert data into geological information at a satisfactory level of precision."

A LITTLE HISTORY

Thomas Edison in 1901 recorded a dip needle anomaly over Falconbridge's first orebody, but it wasn't drilled until 1917. An Electrical Potential Survey was used to discover the Buchans Mine in the 1930s. Ground electro-magnetics resulted in the discovery of the Macdonald Mine in 1944, the Quemont Mine in 1945, the Brunswick No. 6 Deposit in 1952, and the No. 12 in 1953.

Geophysical exploration in Canada really took off with the 1953 Heath Steele discovery by airborne electromagnetic surveying. Then things started to happen - Inco's Thompson Lake Ni-Cu deposits in 1955, Chibougamau discoveries in the mid-1950s, Mobrun 1956, Matagami 1958, Kidd Creek 1962, Matabi 1969, Selbaie 1974, Izok L. 1975, plus a host of others.

A number of the more recent massive sulphide discoveries in Canada have been made at depths beyond the reach of airborne and most ground geophysical methods. Borehole E.M. surveys have been of both direct and indirect assistance either in their discoveries or as a guide in subsequent drilling. These include the Anvil and Isle-Dieu copper-zinc deposits in northwestern Québec, the Winston Lake zinc-copper deposit in north-central Ontario, and the Duck Pond copper-zinc deposit in Newfoundland.

A CANADIAN OVERVIEW

Let us look at some of the airborne and ground data over some of Canada's massive sulphide deposits.

Figure 40.1 shows the original 1958 airborne dual quadrature E.M. system (2300 Hz and 400 Hz) results over the Matagami Mine in north-western Québec, along with a ground gravity profile over the same deposit, as well as later in-phase and quadrature (390 Hz) helicopter results. Also in Figure 40.1 is shown C.A.S. (Canadian Aero Service) results over the Selbaie copper-zinc deposit located west of Matagami.

Figure 40.2 shows a variety of airborne and ground geophysical results over four widely separated deposits in Canada, namely, the Gonder-Izok Lake base-metal deposit in the Northwest Territories, the C and A zones of Heath Steele's copper-lead-zinc mine in New Brunswick, the Destor Lake gold-bearing sulphide deposit of northeastern Ontario, and the Brunswick No. 6 copper-lead-zinc mine in New Brunswick.

In Figure 40.2, airborne Input E.M. is shown over both the Gonder and Detour Lake Deposits, with helicopter low frequency (390 Hz) in-phase and quadrature E.M. responses shown over the Kidd Creek, Heath Steele, and Brunswick No. 6 zones.

Figure 40.3 shows airborne Input E.M., gravity, vertical loop, horizontal loop E.M., and induced polarization over the Iso-Magusi River Deposit in northwestern Québec.

Figure 40.4 shows some geophysical responses over three different Canadian massive sulphide deposits which were most certainly technical successes at the time, but so far haven't had the grade to be economic. The Vangorda Creek lead-zinc deposit (9.4 million tons 8% Pb-Zn plus 1.76 ounces Ag) in the Yukon was outlined very accurately by a gravity survey in 1955 (by the author), but it's still on the shelf, although there is some talk of Curragh Resources mining it soon (some 30 years after discovery). Point Leamington in Newfoundland found in 1971 by an Input E.M. survey is large (15 million tons), but too low a grade (~1% Cu). The Lac Porphyry massive sulphide in northwestern Québec is a good electrical conductor, magnetic, very large (produces a two milligal gravity anomaly) and situated in a rhyolite, yet it's barren.

At Noranda, we have continued an active base metal exploration program in and around a number of our mining establishments, notably at Noranda, Matagami, and Brunswick Mining and Smelting. We are interested in developing more copper and zinc reserves for our mills and smelters.

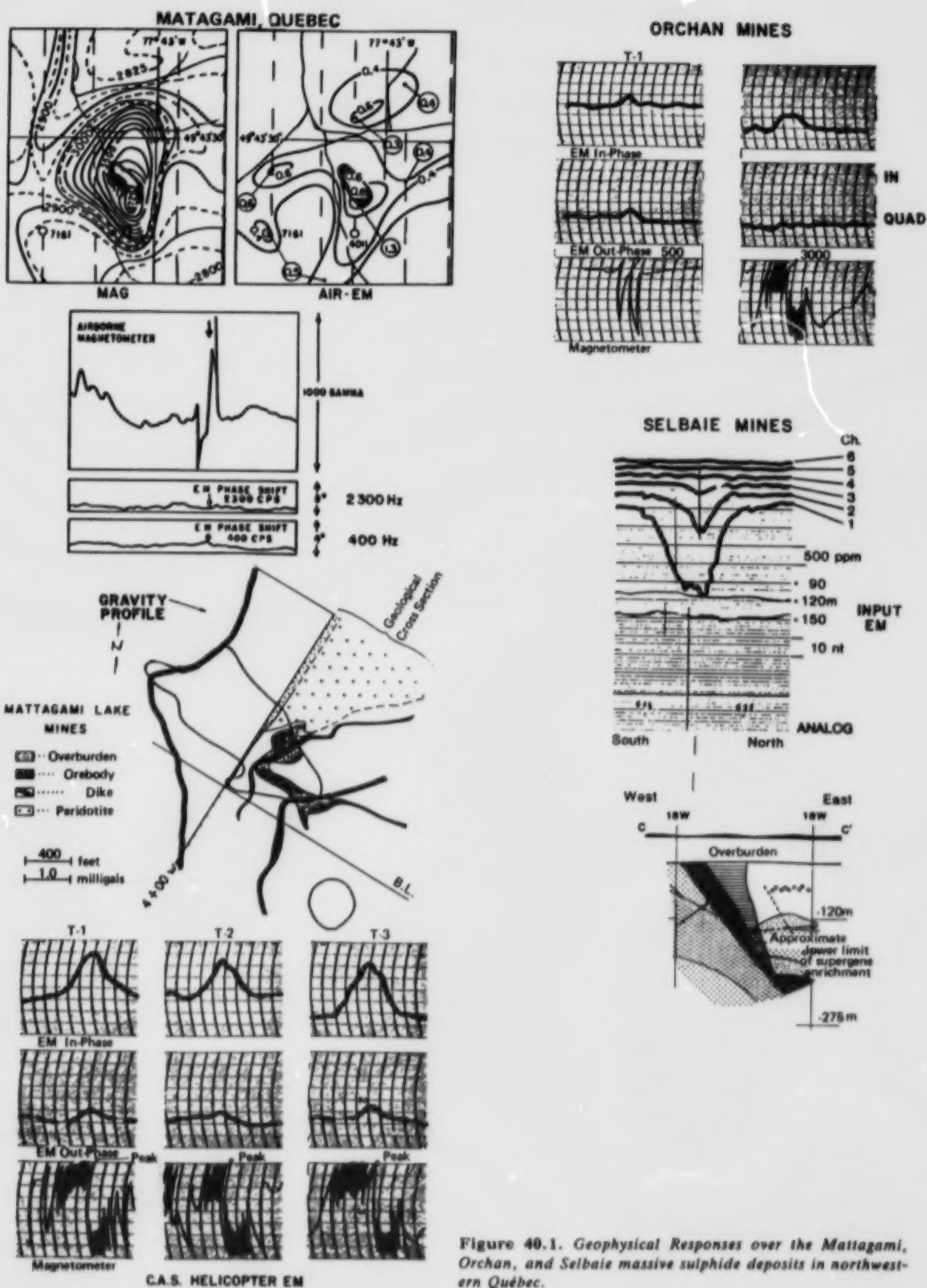
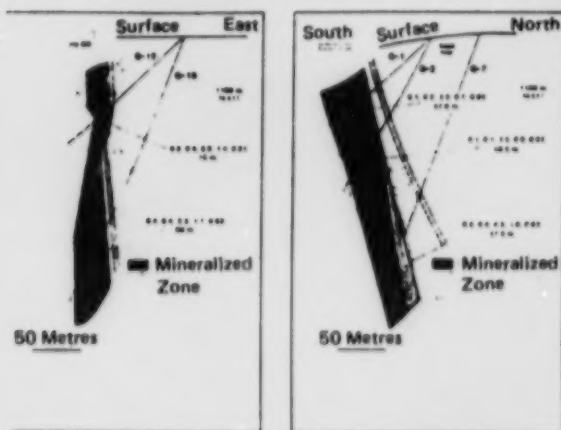
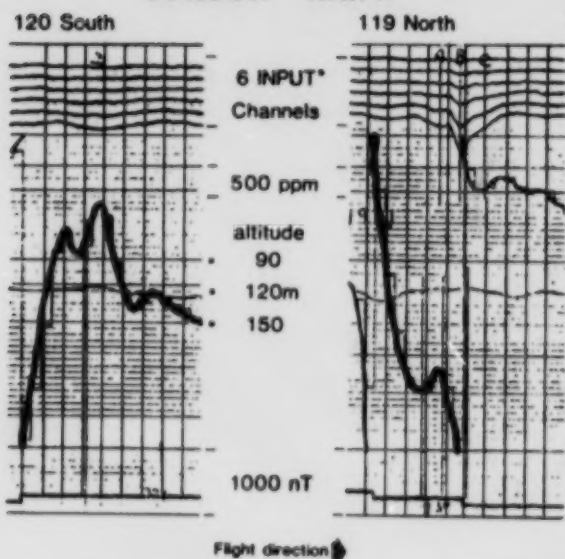
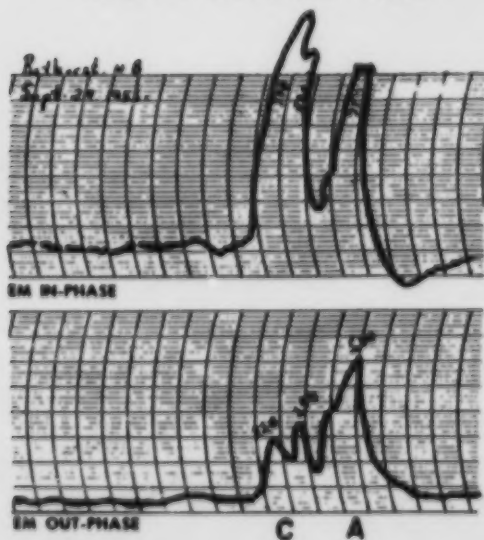


Figure 40.1. Geophysical Responses over the Matagami, Orchan, and Selbaie massive sulphide deposits in northwestern Québec.

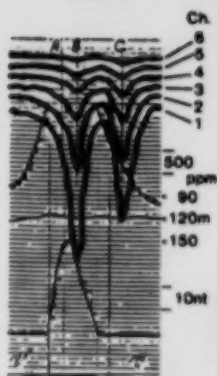
GONDOR N.W.T.



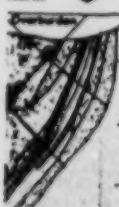
HEATH STEELE N.B.



DETOUR LAKE, ONT.

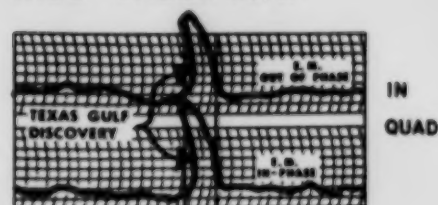


North South



0 25 50 Scale-metres

KIDD CREEK ONT.



BRUNSWICK NO. 6 N.B.

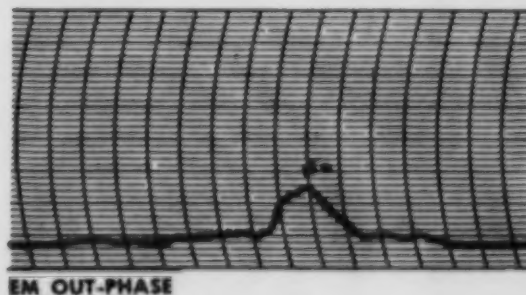
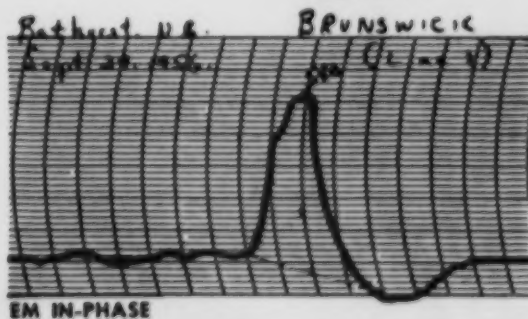
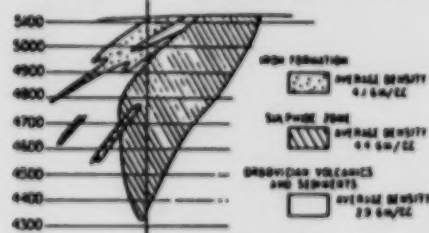
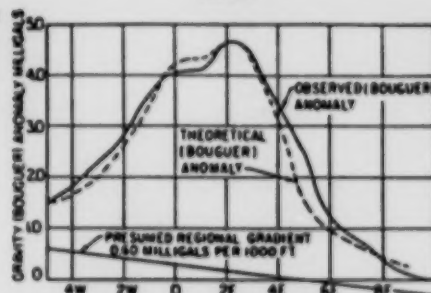


Figure 40.2. Geophysical Responses over the Gondor (Northwest Territories), Kidd Creek, Detour Lake (Ontario), Heath Steele, and Brunswick No. 6 (New Brunswick) massive sulphides.

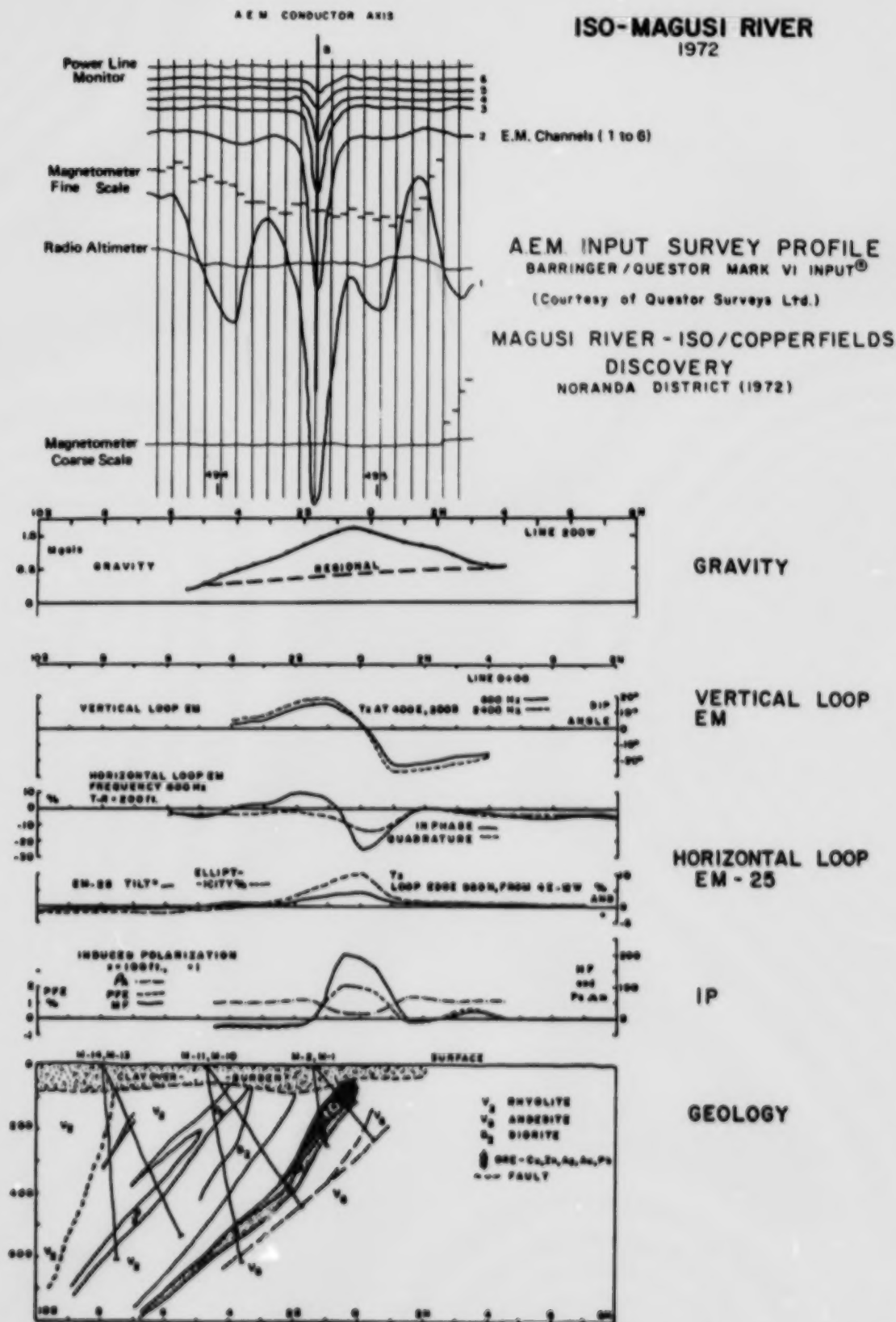


Figure 40.3. Airborne and ground geophysical signatures over the Iso-Magusi River Cu-Zn Massive Sulphide Deposit, Québec.

GEOPHYSICAL RESPONSE OF SOME CANADIAN MASSIVE SULPHIDE DEPOSITS
R. H. PEMBERTON

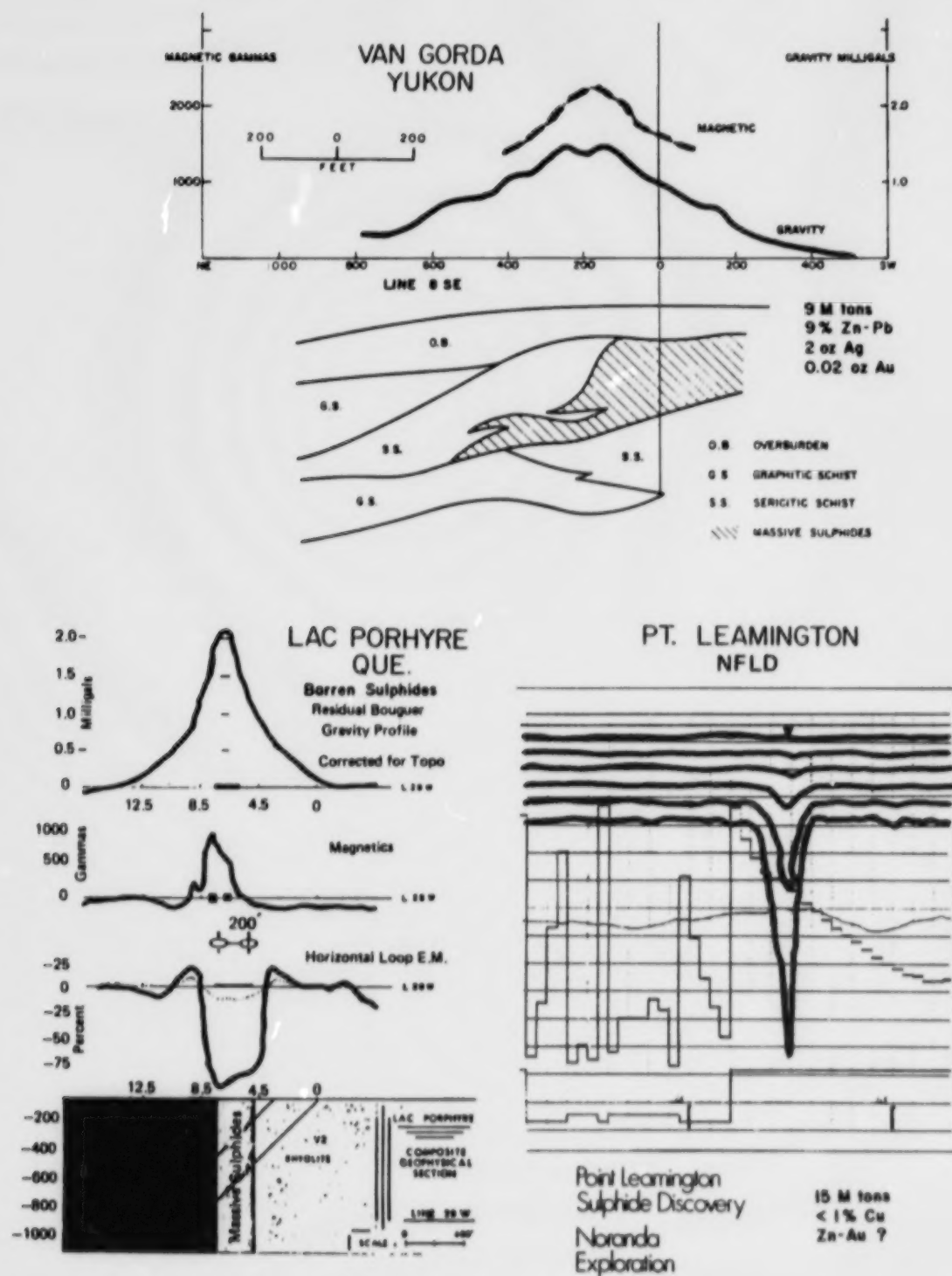


Figure 40.4. Geophysical Responses over three uneconomic massive sulphide deposits in Canada.

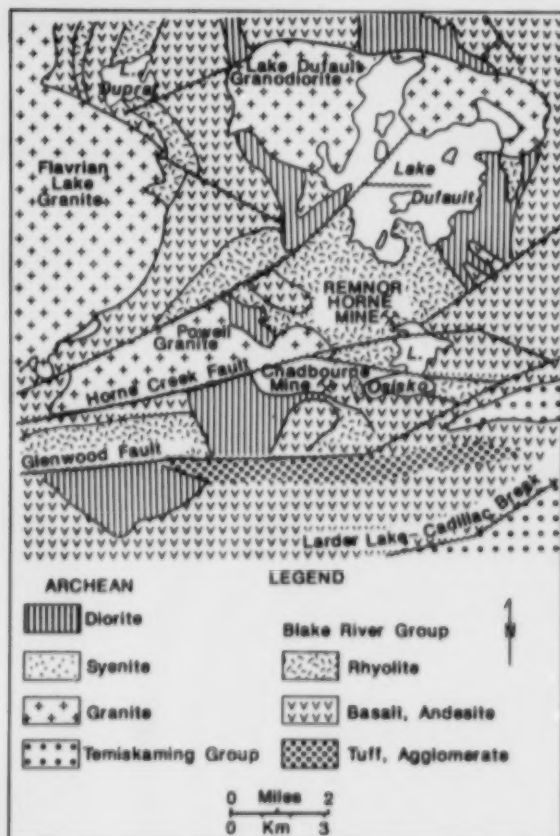


Figure 40.5. Geology of the Noranda area, Québec.

THE NORANDA CAMP

The Noranda Camp was discovered in 1923 by surface prospecting. To date, the Horne Mine itself has produced 60 million tons of 2.2% Cu and 0.177 ounce per ton Au. The mine is no longer producing copper, but is still mining the Remnor gold zone.

The regional geology of the Noranda Camp consists of a central volcanic belt with alternating mafic flows and felsic flows (Figure 40.5).

The largest base-metal deposits in the camp, the Horne and Quemont Mines, occur within a pile of felsic volcanics. These deposits are also the largest gold producers of the camp with more than 10 million ounces of gold from the Horne and just under 2 million ounces from the Quemont Mine.

MINES GALLÉN

The Mines Gallén (formerly Macdonald Mine) volcanogenic massive sulphide deposit, discovered in 1944 by a ground E.M. survey, lies within felsic volcanics completely surrounded by the Lake Dufault Granodiorite only 10 km north of the original Horne

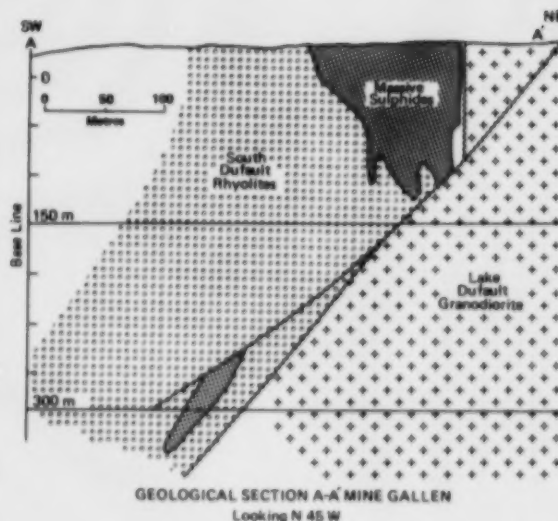


Figure 40.6. Geology of the Mines Gallén Deposit, Québec.

Mine. The deposit consisted of 8 million tons 3% Zn, 24 g Ag, and 1 g Au.

The deposit has a strike length of 275 m, a maximum width of 120 m, and a depth of 150 m (Figure 40.6).

Figure 40.7 shows textbook type horizontal loop E.M., magnetic, and gravimetric results across this deposit.

Figure 40.8 shows the 444 Hz MaxMin horizontal loop E.M. results along with an actual plan outline of the boundaries of the Mines Gallén massive sulphide.

RIBAGO DEPOSIT

The Ribago Deposit is located 5 km northwest of the Horne Mine and occurs at a depth of 2000 feet along the contact between the Amulet andesites and rhyolites.

The deposit consists of 9 million tons possibly averaging 0.5% Cu, but having local concentrations of up to 3 to 4% Cu.

Borehole Pulse E.M. was used to locate off-hole indications of mineralization. Hole 79-2 (Figure 40.9) at 2200 feet shows an off-hole response from sulphides located some 400 feet west of the hole.

Hole 79-3 (Figure 40.10) shows an off-hole response from sulphides lying as far away as 600 feet from the hole.

In this particular situation, it seems reasonable to assume that the borehole Pulse E.M. can safely be employed to locate similar type mineralization as far away as 400 to 600 feet from any of the drillholes in this area. This is important as it means

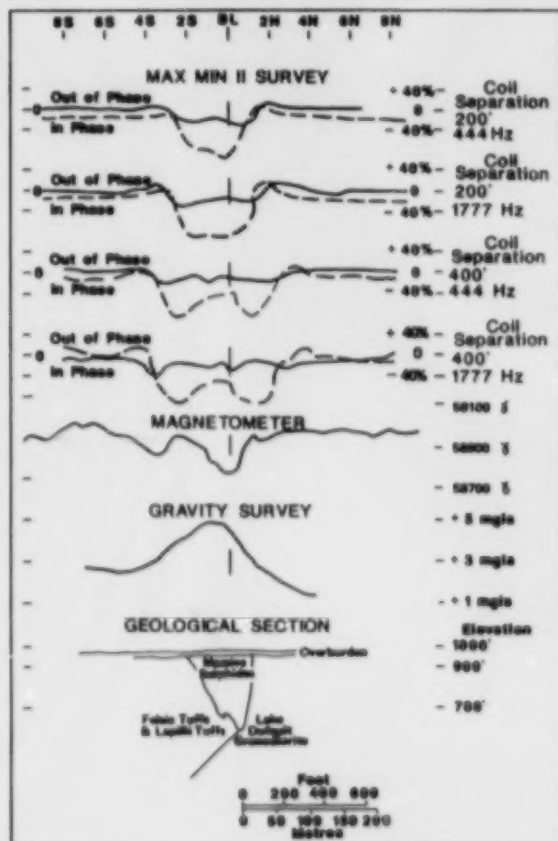


Figure 40.7. Geophysical Responses over Mines Gallen Deposit, Québec.

one can economize or minimize the amount of expensive drilling required to explore the favourable stratigraphy in the area.

THE MATAGAMI CAMP (Figure 40.11)

A total of 40 million tons have been produced from the seven deposits discovered in the Matagami area sector since 1958. Average grade of Matagami's 28 million tons has run 8.3% Zn, 0.56% Cu, 0.85 ounce per ton Ag, and 0.01 ounce per ton Au. Norita and Orchan have both produced 5 million tons of ore. Lesser tonnage has come from the New Hoscoe, Garon Lake, Bell Allard South, and Radiore Mines.

The need to replace depleted zinc ore reserves, the established mine infrastructure, an excellent land position, and a good potential for locating new ore deposits were added incentives in continuing an aggressive exploration program in the Matagami area. This exploration resulted in the discovery of the Isle-Dieu Matagami Deposit in June 1985. This entirely blind new discovery at a vertical depth of

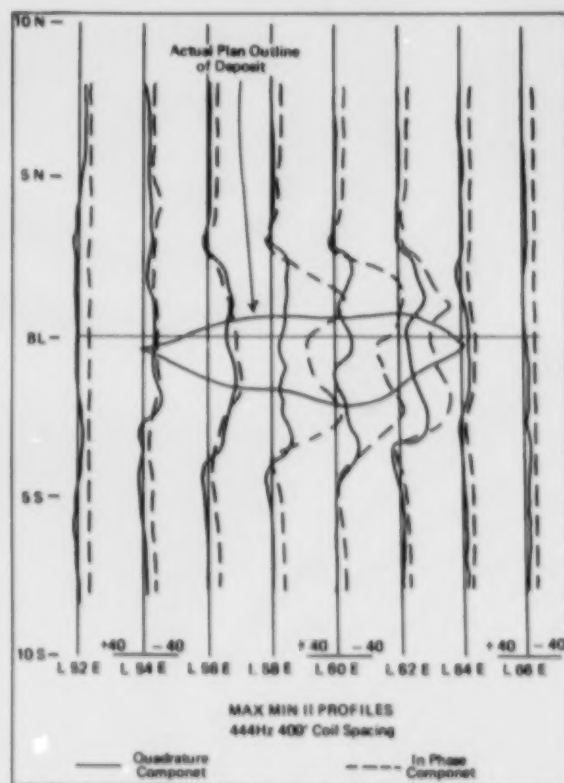


Figure 40.8. MaxMin 444 Hz Responses over Mines Gallen Deposit, Québec.

1350 feet is located only 1.5 km from the present Matagami mill (located 250 km north of Noranda).

The rocks consist of older Watson Lake felsic volcanics overlain by younger Wabassée mafic volcanics, disrupted by a mafic igneous complex. All the rocks have been folded into a broad anticlinal structure about a northwest-trending axis.

The deposits are volcanogenic in origin.

The larger and by far the richest deposits occur along the southern flank of the anticline. Here, the productive horizon is marked by a chert and tuff layer known as the Key Tuffite which occurs as a thin blanket over the ore deposits and shows remarkable continuity.

The productive horizons are entirely covered by 50 to 150 feet of overburden. Because of this thick cover, previous discoveries were made using airborne geophysical techniques and occur near surface (see Figure 40.1). The limited depth penetration of these techniques precluded the discovery of deposits at depths greater than 400 feet. A major program of stratigraphic diamond drilling was initiated early in 1984 to test the favourable horizon at depth as well as the underlying rhyolites for alteration patterns

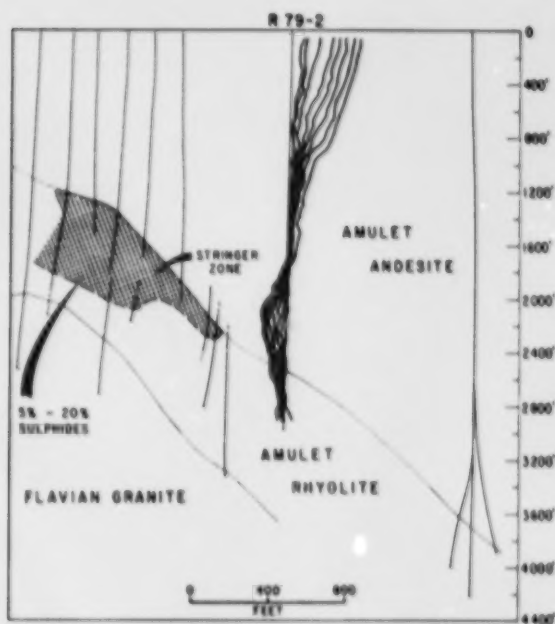


Figure 40.9. Borehole Pulse EM Hole 79-2 - Ribago Deposit, Québec.

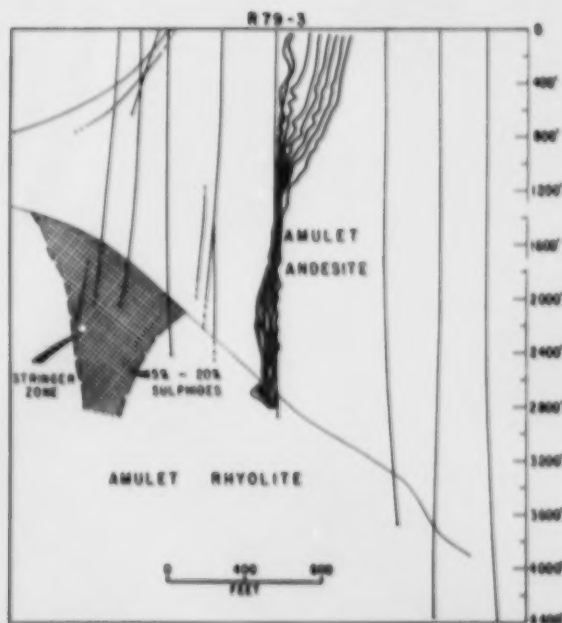


Figure 40.10. Borehole Pulse EM Hole 79-3 - Ribago Deposit, Québec.

similar to those found below the Mattagami and Orchan Deposits.

The second hole drilled intersected 18 feet of good grade ore. To date, 2.5 million tons grading 21.3% Zn, 1.08% Cu, 2.50 ounces per ton Ag, and 0.013 ounce per ton Au have been outlined.

Figure 40.12 is a plan view of the outline of the deposit and the location of discovery hole 85-2. The top of the Isle-Dieu Deposit occurs at a depth of 1350 feet below ground surface.

Figure 40.13 shows the plotted Borehole Crone Pulse E.M. results of channels 2, 4, and 6 for seven holes drilled on Line 18+00W which traverses across the Isle Dieu Deposit.

Only holes 85-2, 85-25, and 85-15 cut through the ore zone. Hole 85-7 lies within 100 feet of good ore, but gives little indication of any sizeable off hole conductor along the Key Tuffite horizon. Holes 86-1, 86-23, and 85-27 pick up the mineralized Key Tuffite horizon and show progressively stronger off-hole responses as one approaches the ore zone. The responses from the holes drilled within the ore produced mixed off-hole, in-hole, and edge type responses. These results certainly reveal that the Isle-Dieu Deposit is not a continuous conductive sheet, but a series of small isolated conductive plates, due to massive non-conductive sphalerite and minor metallic sulphides.

As can be seen in Figure 40.14 (Geological Section of Line 18+00W), after the deposition of the Key Tuffite and sulphides, later intrusion of quartz-diorite dikes split the ore zone in two. All of the rock formations were folded and dip 40° to the southwest.

UTEM Pulse E.M. was bothered by power-line interference and the only possible real anomaly recorded was of the wrong wavelength in keeping with the target depth.

A Controlled Source Audio-Magnetotelluric (CSAMT) survey over the Isle-Dieu Deposit produced only highly questionable results which would not, on its own merit, produce a drill target.

Only a small amount of pyrrhotite occurs in the deposit which is too weak to be seen at surface. Magnetics correlate with gabbroic intrusions and Wabessee andesites in the area.

As for gravity, we calculated that for a 2 million ton deposit at 1300 feet with a density contrast of 1.5 g/cm³ we would get a 0.005 milligal anomaly, so we did not waste our time running an actual gravity survey.

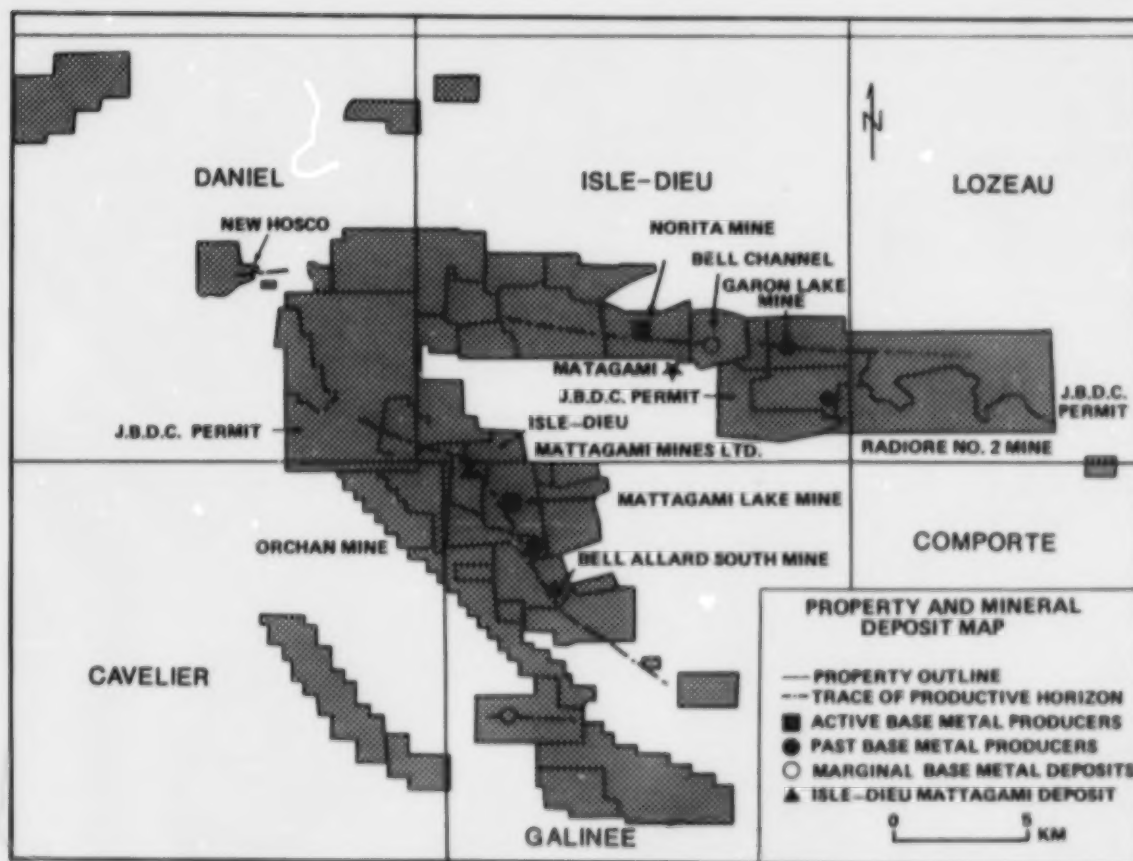


Figure 40.11. Mineral Deposits - Matagami area, Québec.

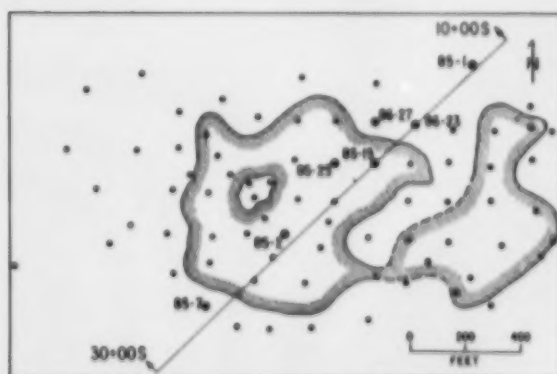


Figure 40.12. Surface plan of Isle-Dieu orebody and location of Line 18+00 W.

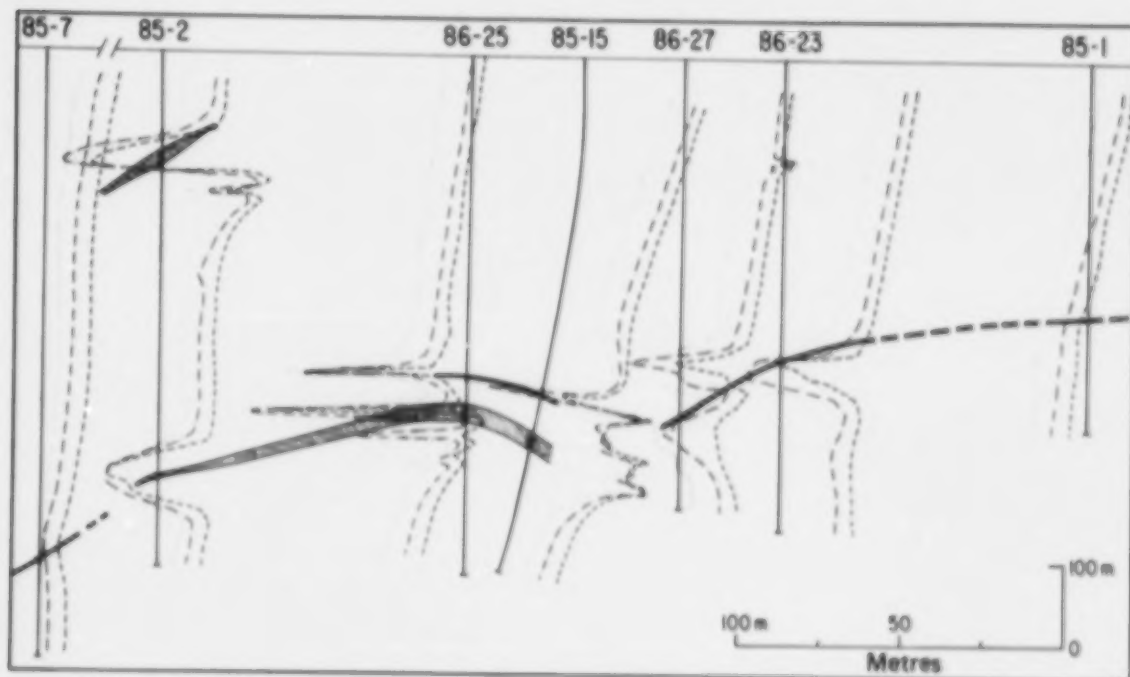


Figure 40.13. Borehole Pulse EM results along Line 18+00 W - Isle-Dieu Deposit.

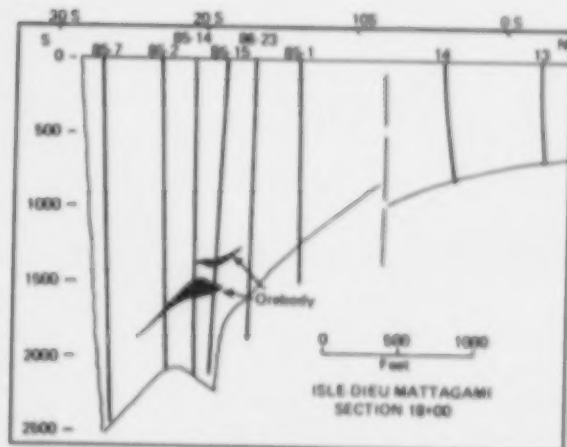


Figure 40.14. Geological Section - Line 18+00 W - Isle-Dieu Deposit.

THE NORITA MINE, QUÉBEC

The original Upper Zone of Norita was discovered in the mid-1960s by a Turam E.M. survey. Recently, the East Zone was discovered by surface drilling at a depth in excess of 2000 feet (see Figure 40.15).

UTEM E.M. was run on L48+00E over the East Zone.

A weak indication at 100S occurs over known sulphides (see Figure 40.16). Peak to peak depth calculations indicate a depth of conductor of approximately 250 feet. Barren sulphides are known at

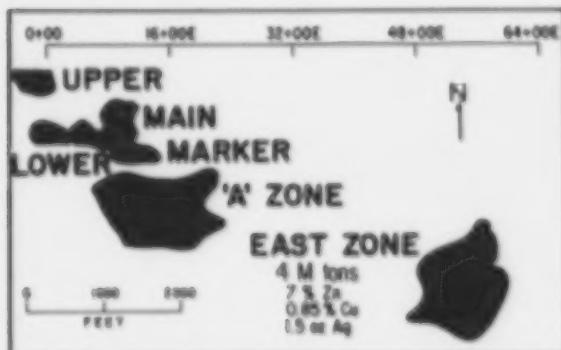


Figure 40.15. Norita Mines Deposits.

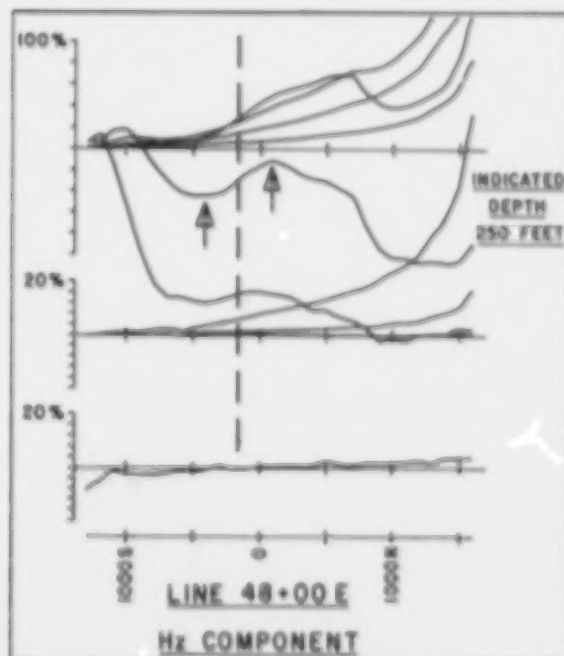


Figure 40.16. Norita Mines UTEM-EM results over East Zone.

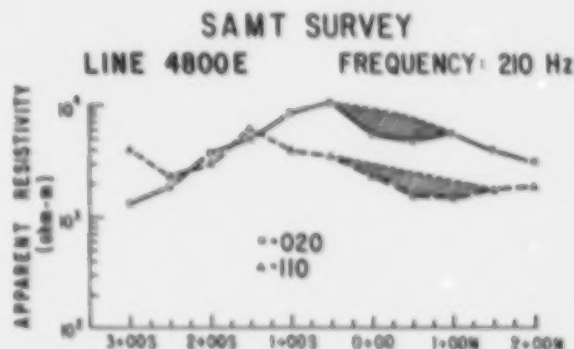


Figure 40.17. Norita Mine Scalar Audio-magnetotelluric EM results over East Zone.

this depth and occur stratigraphically above the mineralized East Zone.

Scalar AMT at 210 Hz (Figure 40.17) shows an anomaly which increases in both telluric directions, which the contractor's interpreter said was indicative of a deep conductor.

A depth calculation based on anomaly curve shape indicates a depth of 250 to 300 feet subsurface.

What we are seeing here, is that geophysics has detected barren conductive sulphides which occur in the same stratigraphic horizon producing ore grades at greater depths. The fact that no economic values were found in shallower drilling is no reason to walk away from the prospect if one has any confidence in the geological model.

THE BOUNDARY DEPOSIT, NEWFOUNDLAND

Noranda became interested in the Central Volcanic Belt in 1973 following initial discoveries of high grade float in the area. Noranda's Point Leamington Deposit lay within this same belt to the northeast and the prolific high grade Cu-Pb-Zn Buchans Deposits lay just to the north. Following a 1975 helicopter E.M. survey, two weak conductors were located which were called the Boundary Zone. Figure 40.18 shows the location of both the North and South Boundary zones detected by the Aerodat E.M. survey in relation to the Duck Pond Deposit located 4 km to the southwest of the Boundary Deposits.

GEOPHYSICAL RESULTS

Figure 40.19 shows horizontal loop profiles at 2400 Hz, gravity, and IP resistivity data. Both the North and South zones dip gently north and south, respectively, off a central rhyolitic dome.

In 1981, subsequent drilling of both North and South zones proved up 500 000 tons of 3.5% Cu, 4% Zn, 1% Pb, and 34 g Ag. Follow-up exploration

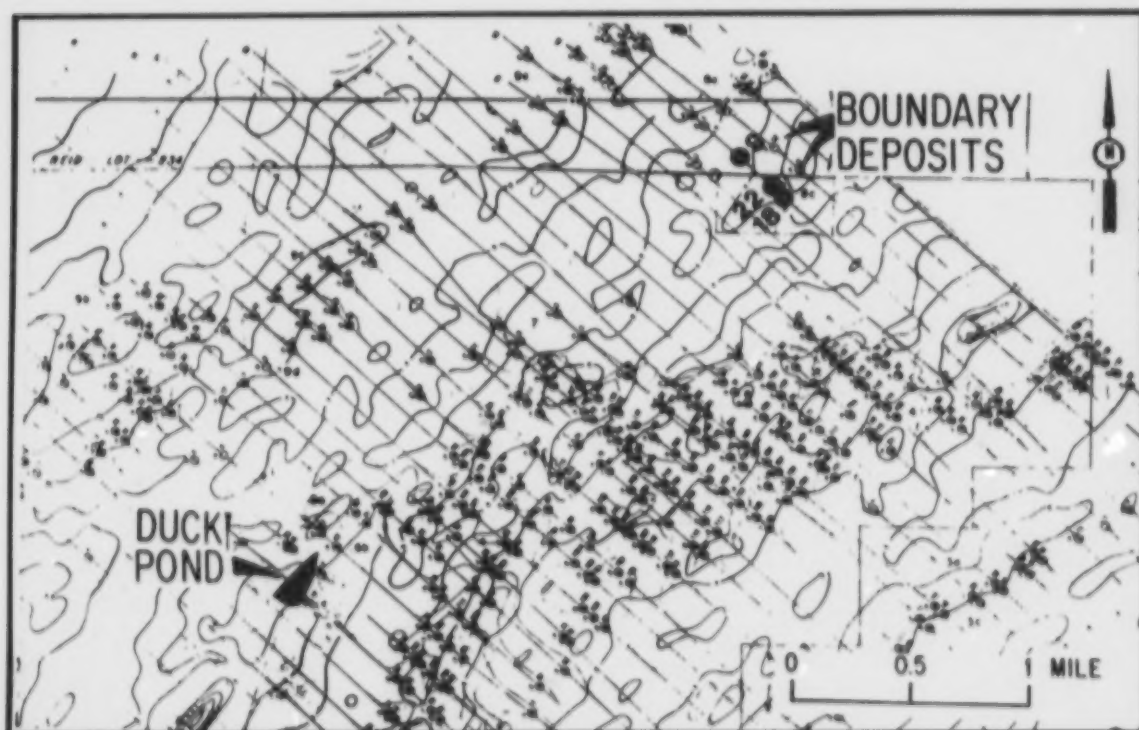


Figure 40.18. Helicopter EM results over North and South Boundary Deposits and location of Duck Pond Deposit to Southwest.

along the favourable belt for a number of years produced little success and encouragement. Conductors drilled located only graphite and barren sulphides. It was not until core analyses and alteration studies suggested that we could be approaching an area which could host economic mineralization at greater depth (if our geological hypothesis was correct!) that a decision to drill deeper holes was made which resulted in the discovery of the Duck Pond Deposit, located 4 km to the southwest of the Boundary Deposit, and at a depth of 1150 feet below surface. Noranda News Releases indicated an approximate strike length of 1250 m, a width of 100 m, and average thickness of 13 m and the zone is open in all directions. Grades are attractive being so far in the order of 3.5% Cu, 1% Pb, 8% Zn, 2 ounces Ag, and 1 g Au.

This was therefore, not a type of program for the faint hearted! It is rather a good example of good geological mapping, keen observation, and a thorough understanding of the volcanogenic processes which can, in certain environments, produce good grade and tonnage ore deposits. Although geophysics helped directly in the initial discovery of the Boundary Deposit, it was of only indirect use in outlining the favourable host stratigraphy farther along

the belt. This is what integrated exploration is all about!

To get back to the Boundary Horizontal Loop Survey, initial horizontal loop results produced a large variety of responses which were difficult to interpret and confusing. Once we realized that we were dealing with a fairly shallow near horizontal conductive plate type model, we undertook an in-house modeling program to examine the effects of depth, plate orientation, sample density, and profile location.

Figure 40.20 shows one such modeled response for such a conductor lying at a depth of 26 m at 444 Hz and 1777 Hz.

ALIASING

The shape of the response curve is dramatically affected by the sample density. If the sample density is not great enough, the response curve will be misrepresented or distorted. This distortion is referred to as aliasing.

Figure 40.21 illustrates "Aliasing" using the 1777 Hz quadrature modeled results as an example.

In order to accurately represent any response curve, it must be sampled at twice the highest frequency part of the response. Using the model as an

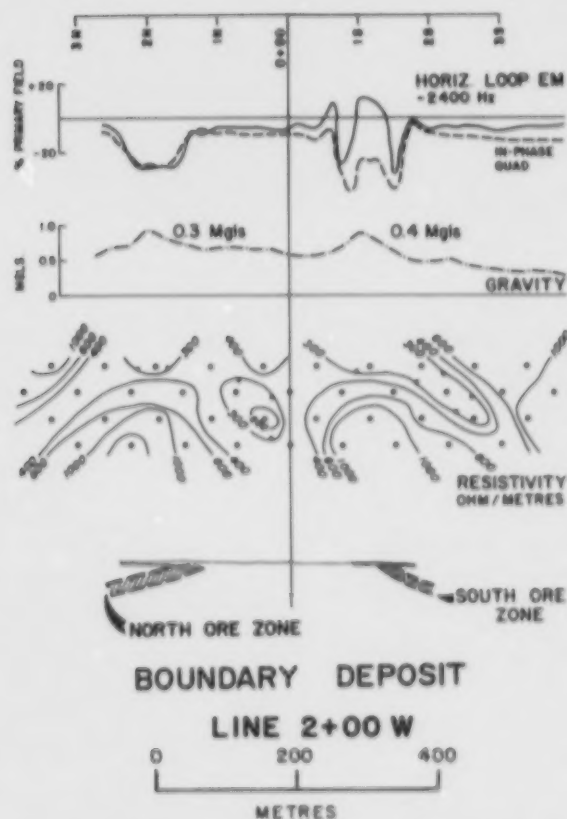


Figure 40.19. Ground Geophysical Results over North and South Boundary Deposits, Newfoundland.

example again, it can be seen that a sampling frequency of approximately 35 m must be used to accurately represent the response curves.

Curves A and B are sampled at 50 m intervals. Notice that just a slight difference in positioning of the sample points can have a profound effect on the response curves. Curve A would lead to the correct dip direction, but Curve B would actually lead one to believe that the plate dips in the opposite direction.

Curves C and D are sampled at 100 m intervals. They both misrepresent the response as that of a near vertical plate. Sample positions showing in C would lead to the opposite dip direction of those in D.

Modeling of the response over the end of the plate showed that the high amplitude negative flanks are diminished and the broad central high is actually accentuated.

Modeling of the response off the end of the plate shows that only a central high is present and that its amplitude falls off so fast that detection becomes very difficult.

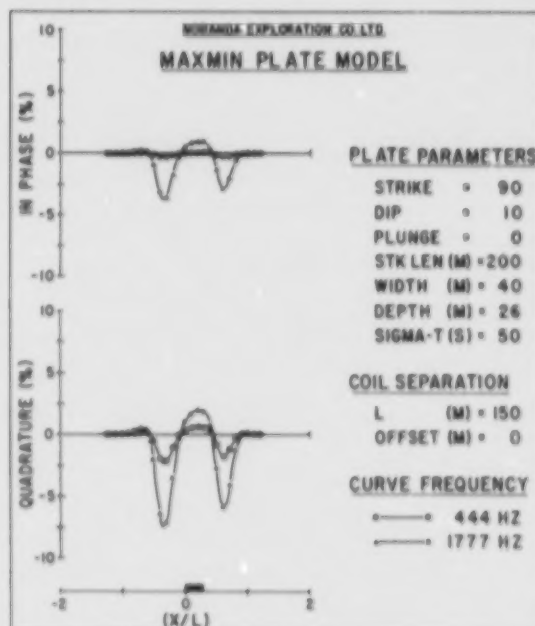


Figure 40.20. Horizontal Loop EM modeled results over Horizontal Conductor.

This modeling illustrated the necessity to detail anomalies produced by flat lying bodies with small widths and short strike lengths.

From a practical viewpoint, if the area is good enough geologically to explore, then it is obligatory to select the correct survey specifications to detect the target you are trying to find. Otherwise you are short changing yourself.

If you want to discover a Duck Pond type deposit in a Duck Pond geological setting, then every step along the way leading to such a discovery is critical, including the selection of the correct geophysical specifications, even though they were used on an isolated but related target 4 km away.

BRUNSWICK MASSIVE SULPHIDES

The Brunswick Camp, discovered in 1952 and 1953, produced 12 million tons from the No. 6 Deposit and over 50 million tons from the No. 12 Deposit which has still over 100 million tons of reserves over 12% combined Pb-Zn, 3 ounces Ag, and 0.33% Cu.

Heath Steele produced 18 million tons of lesser grade and has marginal reserves of 16 million tons of 6.6% Pb-Zn, 1.2% Cu, and 1 ounce Ag.

The area has been worked for over 35 years and has experienced extremely intensive and extensive exploration using every imaginable geophysical technique.

However, we are still finding new reserves of a grade which should be economical to mine.

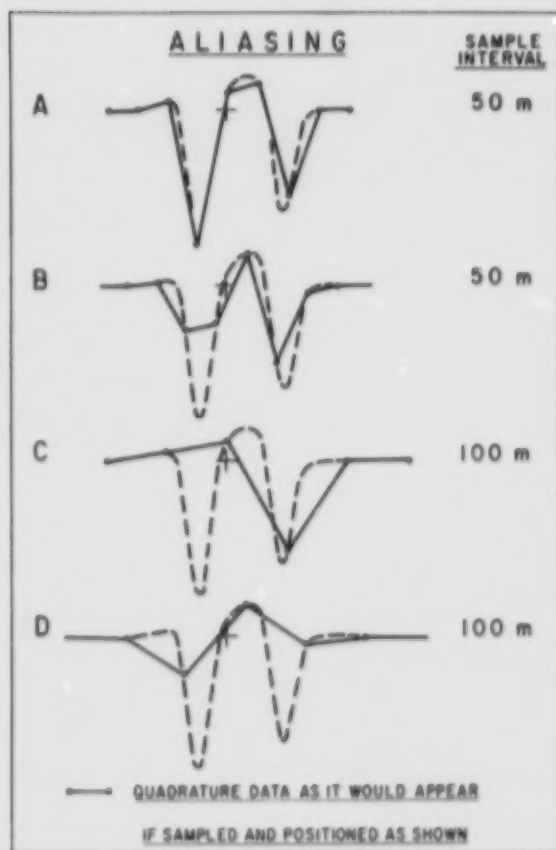


Figure 40.21. The Aliasing Effect.

We have certainly used conventional airborne and ground E.M. successfully and many of these conductive targets have produced mines. Even though the deposits we discovered have been good conductors due to their sufficiently high metallic sulphide content, we are finding that some deposits of high zinc content noticeably lack a high enough metallic sulphide content to act as anything other than a rather poor conductor.

Figures 40.22 and 40.23 are an example of one such deposit in New Brunswick where the Horizontal Loop expression at 444 and 888 Hz is minuscule. However, at the higher frequencies all the way up to 14 080 Hz, we see a clearly defined anomaly developing. Fortunately of course, we are dealing with an area of uniform high resistivity background or low geological background noise; such data having been observed during the course of previous surveying in the area which enabled us to judiciously select an optimum sequence of exploration methods and approaches.

This is but one example of a successful change in the geophysical approach to ore finding brought

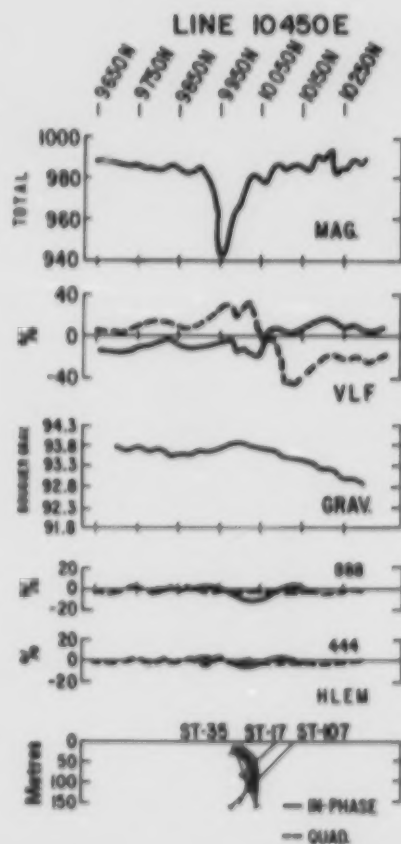


Figure 40.22. Geophysical Results over a zinc-lead-copper deposit in New Brunswick.

about by a progressively improved understanding of the geological target and host environment.

A FINAL COMMENT

The geophysical case histories or examples presented in this paper include a fairly wide spectrum of geophysical methodologies. In the early 1950s, 1960s, and even up into the 1970s, many discoveries were made basically by flying airborne E.M. over what were considered to be favourable volcanic terrains (witness Mattagami, Heath Steele, Kidd Creek, and Izok Lake, for instance). As airborne methods have limited depth detection capabilities, the exploration fraternity has had to pay much more attention to the integrated exploration approach utilizing all the clues one can gather from all sorts of indirect data of a geophysical, geochemical, or geological nature. It has paid off handsomely too in many cases, as can be seen in the case of Isle Dieu and Duck Pond discoveries.

Geophysics has changed a lot in the last 25 years, but a lot of geophysicists don't know the ex-

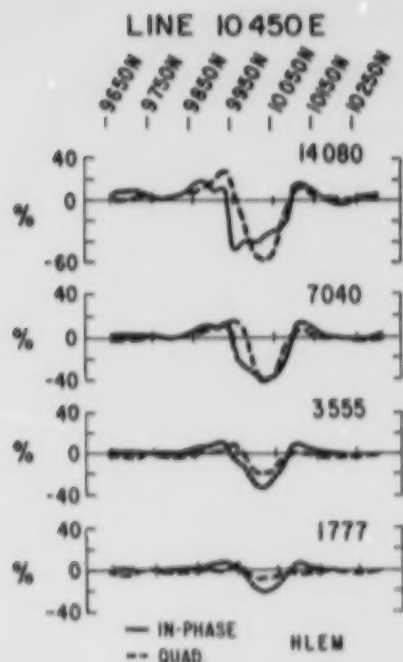


Figure 40.23. Horizontal Loop EM results over same deposit as in Figure 40.21.

tent to which geological information has changed in the same period itself.

New ideas are the fuel of exploration.

In conclusion, I can't say it any better than Weimer (1987) said in a recent interview.

"The history of science clearly records—that at every point in time man has accepted as truth some incorrect concepts. Some of the concepts in widespread use today are undoubtedly wrong; we just don't know which ones they are yet. The challenge to each generation of management is to accept the change and not hinder the application of new scientific thought."

ACKNOWLEDGMENTS

I would like to thank Noranda Exploration Company, Limited for permission to use company data presented in this paper. I would also like to thank and acknowledge the efforts of many of Noranda Exploration's staff who provided much of the data presented herein, and in particular Mr. Ian Atkinson, Mr. Denis Francoeur, and Mr. Ken Robertson.

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41. Structure of the Witwatersrand Basin Derived from Interpretation of Aeromagnetic and Gravity Data

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ABSTRACT

The Witwatersrand Basin is situated roughly centrally on the Kaapvaal Craton of southern Africa. It essentially comprises a sequence of argillaceous (West Rand Group) and gold- and uranium-bearing arenaceous (Central Rand Group) sediments, reaching thicknesses of up to 5000 m. Most of the basin is overlain by rocks, often attaining thicknesses of as much as 3000 m, belonging to the Ventersdorp Supergroup, and the Transvaal and Karoo Sequences.

In this paper, integrated gravity and magnetic interpretation is directed towards structural mapping of the Witwatersrand Basin over an area of roughly 300 by 350 km. The magnetite-rich rocks of the West Rand Group have positive density and magnetic susceptibility contrasts with respect to both the immediate basement and overlying strata. These rocks thus constitute an excellent geophysical marker.

Published Government aeromagnetic data, totaling over 100 000 line km and covering the Witwatersrand Basin, have been leveled, corrected for the International Geomagnetic Reference Field and gridded at a 500 m interval. The Bouguer gravity data set over the same area comprises some 13 500 gravity stations. Interpretation of these data sets follows two courses: firstly, structural trend mapping is achieved through the application of image processing techniques; secondly, inversion techniques are applied to yield depths to magnetic sources or anomalous masses. Derived depths are used, together with available borehole data, as constraints for forward modeling along selected profiles.

A revised suboutcrop map of the basin, showing new or more accurately defined extensions and structural detail is presented. Isodepth contours to the base of the Central Rand Group are revised on the basis of an integration of the geophysically derived depths with published borehole and mine data. New structural concepts with local and cratonic implications and based on an integration of the geophysical results with outcrop, borehole, and mine information, are discussed. In particular, a magnetite-rich layer is identified within the granitic basement, occurring roughly 8 km below and subparallel to the base of the basin. The layer, termed the Vredefort Discontinuity, is an excellent geophysical marker, facilitating mapping of crustal structure associated with the basin.

INTRODUCTION

Rocks of the Witwatersrand Supergroup, constituting the Witwatersrand Basin and associated outliers, occur in the central southeastern part of the Kaapvaal Craton (Figure 41.1). The main basin extends roughly 350 km along a northeast-trending major axis and roughly 200 km in width along an orthogonal minor axis. A century of exploitation has seen the development of some 150 gold mines of which roughly 30 also yield uranium. In terms of value of metal recovered, the Witwatersrand Basin must rank as the most valuable mineral deposit yet found.

Four phases of exploration, each emphasizing a particular approach or technique and signifying the discovery of major new deposits, can be recognized in the history of the Witwatersrand goldfields (Pretorius 1986), i.e. banketting, or the tracing of outcrops, from 1886 to 1895; diamond drilling from 1895 to 1930; geophysics in the form of magnetic and gravity surveys, from 1930 to 1960; and sedimentology from 1960 to 1980. Since 1980, a fifth phase, emphasizing an integrated geological and geophysical approach has evolved. With this approach, structural geology, image processing of aeromagnetic and gravity data, and reflection seismic techniques together play a key role in the exploration, and in the understanding of the evolution of the basin. The application of geophysics to gold exploration and the very significant role which geophysical methods have played in this regard have been discussed by Roux (1967), Campbell and Peace (1984), Van Zijl (1986), and C.C. Pretorius *et al.* (see Paper 22, this volume).

Over 90 percent of the basin is buried beneath younger rocks, often to depths in excess of 3000 m. This fact has militated against the accurate delineation of the shape, configuration, and boundaries of the basin. Pioneering work was, however, done by Borchers (1964) who compiled a map on the basis of outcrop, mining, and diamond drilling data, showing the surface and subsurface geology of the Witwatersrand Basin. A more recent map, employing a large volume of additional information derived from mining operations, diamond drilling and, in part, geophysics, was produced by Pretorius *et al.* (1986). This later synthesis reflects a major improvement on Borchers' (1964) original work. Both maps are, however, limited in accuracy in those regions outside the mining lease areas, particularly where little or no drilling has been conducted.

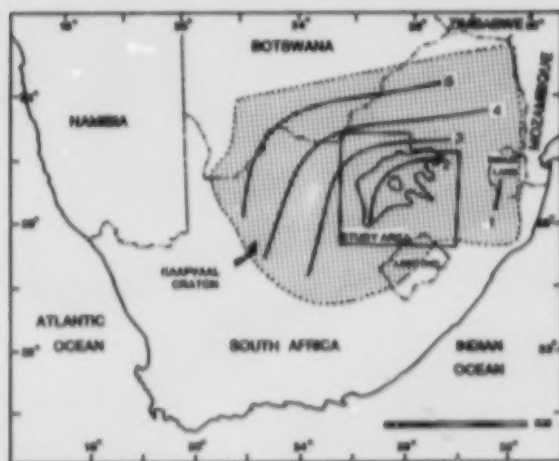


Figure 41.1. Localities of the study area and of the depositional axes of the major Proterozoic basins on the Kaapvaal Craton (after Pretorius 1976): 1 = Pongola Basin; 2 = Witwatersrand Basin; 3 = Ventersdorp Basin; 4 = Transvaal Basin; 5 = Waterberg Basin.

It was the aim of this study to refine the regional mapping of the basin through a rigorous qualitative and quantitative interpretation of the available aeromagnetic and gravity data covering the basin and environs. For this purpose, the gravity and magnetic data sets were compiled in a form suitable for digital image processing. A number of transformations were applied to the data using mostly the computer facilities and potential field software of the United States Geological Survey in Denver, U.S.A. These include: data stretching; edge enhancement; upward continuation; gaussian smoothing; apparent sun-shading from various azimuths; and the delineation of contact positions on the basis of pseudo-gravity data. In addition, two automatic interpretation techniques, based on an Euler depth technique (Thompson 1982), were implemented and used to calculate depths to the sources of magnetic and gravity anomalies throughout the Witwatersrand Basin (Wilsher 1987). The results were used to upgrade the map of Pretorius *et al.* (1986) to one in which major contributions have been made in the delineation of faults and boundaries of the depository, and depth contours of the base of the Central Rand Group. New insights into the structure of the basin are discussed on the basis of the interpretational map.

GEOLOGY OF THE WITWATERSRAND BASIN AND ENVIRONS

REGIONAL SETTING

The Witwatersrand Basin forms part of a chronological sequence of five Proterozoic basins situated on

the Kaapvaal Craton. Strata of the Witwatersrand Supergroup succeed the oldest of these basins, namely the Pongola Sequence, and are, in turn, followed by strata of the Ventersdorp Supergroup, the Transvaal Sequence, and the Waterberg Group. Pretorius (1976) has shown a progressive migration with time of the depositional axes of the five basins towards the northwest (Figure 41.1). He also identified two parallel northwest-trending geanticlines about which a major change in direction of the depositional axes of the five basins occurs.

Only rocks of the Witwatersrand and Ventersdorp Supergroups and Transvaal Sequence are preserved within the study area. The latter two units together with a widespread development of Phanerozoic rocks of the Karoo Sequence make up an extensive succession of cover rocks, both laterally and in depth, blanketing roughly 90 percent of the Witwatersrand Basin. The granitic basement, on which the Witwatersrand Supergroup rests, is exposed centrally within the basin in the prominent Vredefort Dome; and in an arcuate trend to the northeast in the Devon Dome, to the north in the Johannesburg Dome and along the northwestern margin of the basin (see Figure 41.6).

AGE RELATIONSHIPS AND LITHOSTRATIGRAPHY

The Witwatersrand Supergroup comprises rocks of the West Rand and Central Rand Groups. The Dominion Group, which was once regarded as stratigraphically equivalent to the Pongola Sequence, is now considered to be restricted to the region of the study area and to succeed the Pongola Sequence (SACS 1980). The andesitic lavas of the Dominion

Group are considered to form a protobasinal phase of the Witwatersrand sediments overlying them (Tankard *et al.* 1982). Recent work on the Dominion Group rocks has yielded ages of between 3000 Ma and 3100 Ma (H.J. Welke, University of the Witwatersrand, Johannesburg, personal communication, 1987), superseding a U-Pb age of 2820 Ma derived by Van Niekerk and Burger (1969).

The full succession of Witwatersrand strata is not developed throughout the basin due to unconformable relationships of some of the units and to erosional removal in other regions (Pretorius 1976). A generalized lithostratigraphic column of the West Rand and Central Rand Groups, which succeed the Dominion Group, is given in Figure 41.2. The column is derived from the northwestern margin of the basin.

The West Rand Group is divided into three subgroups, i.e. the Hospital Hill, Government, and Jeppetown Subgroups. It comprises a succession of alternating quartzite and shale lithologies reaching a total thickness of up to 5000 m. Because particular horizons may be traced throughout the basin, e.g. the highly magnetic Water Tower Slates, Contorted Bed, and West Rand Shales, the deposition is considered to have taken place in a marine shelf environment (Tankard *et al.* 1982).

The overlying Central Rand Group is divided into the Johannesburg Subgroup, the Booyens Shale Formation, and the Turffontein Subgroup (SACS 1980). This group consists essentially of coarse-grained arenite and minor amounts of shale, silt, and lava; attaining a maximum thickness of up to 3000 m (Tankard *et al.* 1982). Gold and ura-

nium mineralization is found in various Central Rand horizons, and is interpreted as having originated from sources close to the depository, entering the basin in fluvial fan-type deposits (Pretorius 1976).

The Ventersdorp Supergroup, which overlies the Witwatersrand strata, comprises primarily a succession of volcanic rocks with some sedimentary horizons. The andesitic lavas are considered to have erupted along tensional faults caused by the subsidence of the Witwatersrand Basin under the weight of its contents (Tankard *et al.* 1982). Stanistreet and McCarthy (1986), in discussing the control of the Rietfontein Fault System along the northern margin of the basin, suggested that localized acid volcanism of the Ventersdorp Supergroup may have accompanied graben development. As a consequence, the floor onto which the Ventersdorp rocks were emplaced constitutes an often highly undulatory, fault controlled, surface. This factor is of considerable importance to geophysical modeling, particularly with gravity data, and, unless the surface is constrained by drilling information, severe ambiguities may result during interpretation.

Armstrong *et al.* (1986) gave two ages for the volcanic rocks, i.e. 2699 ± 16 Ma (U-Pb on zircon crystals) and $2350 \pm 160-180$ Ma (Pb-Pb on whole-rock samples). The former age is considered to be more reliable (H.J. Welke, University of the Witwatersrand, Johannesburg, personal communication, 1987). The period of deposition of the Witwatersrand Basin sediments, which has not been fixed successfully by direct age measurement, may therefore be bracketed between 2700 Ma and 3000 Ma on the basis of the most recent geochronological work.

TECTONIC EVOLUTION OF THE BASIN

Several models have been put forward with regard to the evolution and structural framework of the Witwatersrand Basin. A full review of these is beyond the scope of this text and only a brief résumé of current thinking follows.

In considering the evolution of the Witwatersrand Basin, most theories fall within one of two scenarios generally applicable to intracontinental sedimentary basin development, i.e. rift or foreland basins. Pretorius (1976) and Minter (1978) explained the tectonic evolution of the basin in terms of extensional tectonics or rifting, while Burke *et al.* (1986), and Winter (1986), suggested that there was more evidence to support the hypothesis of collision tectonics and foreland basin development.

Pretorius (1975, 1976, 1981) presented a model in which Witwatersrand strata were laid down in a structurally controlled, yolked-basin or half-graben, with a fault-bound northwestern margin and a more gentle, downwarped, southeastern edge. He concluded that the basin was a shallow water lake or inland sea during the widespread deposition of the

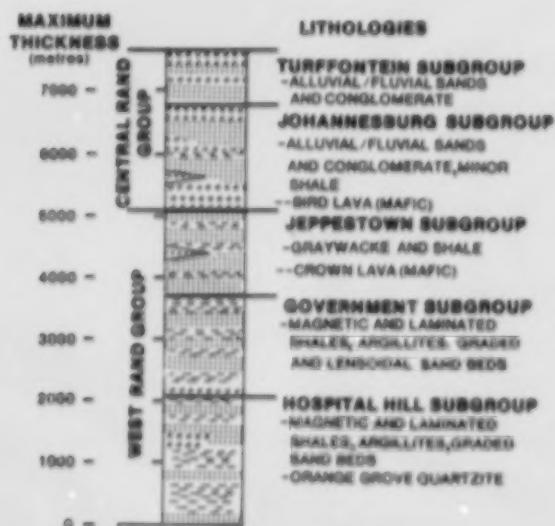


Figure 41.2. Generalized stratigraphy of the Witwatersrand Supergroup (after Burke *et al.* 1986).

West Rand Group sediments. The Central Rand Group sediments were, however, laid down during a structurally unstable period which followed, with sedimentation taking place in the form of fluvial fans, in the downwarps between faulted basement domes. The model proposed by Minter (1978) suggested that the basin can be accounted for by epeirogenic tilting and warping, with granite doming around the basin being responsible for basin closure. Burke *et al.* (1986) viewed the Witwatersrand Basin as a foreland trough which developed on the Kaapvaal Craton in response to loading of the crust by orogenic activity to the north. Subsidence, and deposition of Witwatersrand strata occurred during continental collision between the Kaapvaal and Zimbabwe Cratons.

Another tectonic model is one of wrench tectonics (Stanistreet *et al.*, in press) implying plate interaction within the Kaapvaal Craton at the Archean-Proterozoic boundary. In this model, the northern boundary, and possibly the western boundary, of the basin are considered to have been created by cratonic-scale strike-slip fault systems. These fault systems are characterized by pull-apart basins of immature sediments, narrow slivers of foreign stratigraphy, and marginal convex-upward thrusts, explaining many such features seen along these two boundaries.

GEOPHYSICAL DATA BASE

PHYSICAL PROPERTIES

The persistent magnetic shale horizons of the West Rand Group are useful for mapping the disposition of these strata using the magnetic method. The low-

est magnetic unit is the Water Tower Slate, located roughly 300 m above the basement contact. The Contorted Bed and West Rand Shale magnetic units are situated roughly 300 m above the Water Tower Slates. All of these units are highly magnetic making them readily detectable even when buried to depths of several thousand metres. Their magnetic susceptibility range, derived from Roux (1980) is presented in Table 41.1. Jackson (1982) has reported remanent directions of magnetization which correspond to a resetting event associated with the intrusion of the Bushveld Complex at approximately 2000 Ma. An average direction is given in Table 41.1.

The West Rand Group sediments are also dense with respect to the basement rocks and the overlying Central Rand sediments. This low-high-low pattern of density, in the succession of basement, West Rand Group and Central Rand Group is important for interpreting gravity data. Higher density contributions which complicate this pattern arise from the overlying Ventersdorp lavas and Transvaal Sequence dolomites and shales; and from variations within the granitic basement. Average density values for the above-mentioned units are given in Table 41.1.

Of note is the physical property variation within basement rocks as indicated in Table 41.1. Stepto (1979) reported a density contrast of roughly 200 kg/m³ in his modeling of upper and lower crust in the basement core of the Vredefort Dome.

Corner *et al.* (1986b) required the indicated susceptibility values (Table 41.1) to constrain forward models of a magnetite-rich granitic layer separating upper and lower crust, here termed the Vredefort Discontinuity (after Hart and Andreoli

TABLE 41.1. PHYSICAL PROPERTIES OF ROCKS WITHIN THE STUDY AREA (after Roux (1976, 1980), Smit and Maree (1966), Durrheim (1978) and Jackson (1981)).

LITHOLOGICAL UNIT (in geochronological sequence)	DENSITY (kg. m ⁻³)	MAGNETIC SUSCEPTIBILITY (S.I. units)
Pretoria Group	2850-2900	0.0
Transvaal Dolomite	2850-2890	0.0
Ventersdorp Lavas	2800-2900	0.0
Central Rand Group	2630-2660	0.0
West Rand Group**	2750-2830	0.05 - 0.2
Basement-Upper Crust	2650	0.004
Basement-Vredefort Discontinuity	2680-2690	0.01 - 0.05 *
Basement-Lower Crust	2680-2690	0.0

* These values are either assumed from published values typical for such rock types or are adapted from forward modeling constraints.

** May have a remanent magnetisation component. (Dec. = 20° Inc. = ± 55°).

Zero susceptibility values are assumed for extremely low mean bulk susceptibilities of the indicated units.

1986). These were derived from measurements made by Jackson (1982).

It should be stressed that the available physical property data base for lithologies within the study area is, in general, poor.

AEROMAGNETIC DATA SET

Aeromagnetic data covering the Witwatersrand Basin were gathered by contractors, for the Geological Survey of South Africa, as part of a national program of countrywide coverage. The area represented by Figure 41.3 was covered by six surveys during the period from 1966 to 1981 (Wilsher 1987). Total field data were collected along north-south flight lines at a nominal terrain clearance of 120 m, flying at 240 km/hr and using a sampling interval of one second. The flight line spacing was 1 km and perpendicular tie-lines were flown every 10 km.

In order to facilitate digital transformation, the data were flight-line leveled and block leveled, thus establishing a common datum for all the surveys. A regional field was subtracted from the data using the 1982 International Geomagnetic Reference Field (IGRF) formula. A regular 500 m grid was interpolated by a cubic spline method in the Universal Transverse Mercator (UTM) projection, about the 27° meridian. The effects of surface and shallow subsurface noise, arising primarily from dolerite sills, was investigated, using power spectral analysis by Rodney (1985) and Wilsher (1987). It was found that the 500 m grid in fact aliased much of this source of noise without any significant effect on the

deeper sources of interest arising from the Witwatersrand strata.

BOUGUER GRAVITY DATA SET

The gravity data (Figure 41.4) were collected from a number of regional and detailed surveys conducted by the University of the Witwatersrand; the Geological Survey of South Africa; the Institute of Geological Sciences, Great Britain (Burley *et al.* 1982); and the mining and exploration companies cited in the "Acknowledgments" section. Most of the data were gathered along roads with a maximum station interval of approximately 3 km. The majority of station elevations were determined barometrically and the measurements reduced using the Geodetic Reference System 1967 formula (Woollard 1979). Wilsher (1987) described in detail the procedures used for merging and editing the data sets. A total of 13 500 stations was finally accepted for the compiled data set with an average error of ± 1.62 mgal (Wilsher 1987). The data set was gridded at a 1000 m interval and the UTM projection utilized.

DATA PROCESSING AND INTERPRETATION

DATA PROCESSING

A number of potential-field transformations were applied to the data and maps were prepared of the resulting data sets at scales suitable for comparison with published geological maps.

- The magnetic data were initially upward continued by one grid interval, i.e. 500 m, in order to reduce the noise due to near surface sources still remaining after gridding. This level of continuation did not significantly reduce resolution of the deep-seated structures arising from the basin

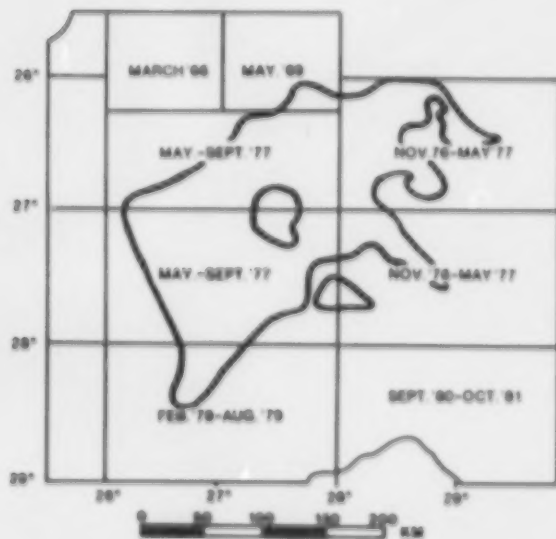


Figure 41.3. Localities and acquisition dates of the various aeromagnetic survey blocks covering the Witwatersrand Basin. The basin perimeter is shown for locational purposes.

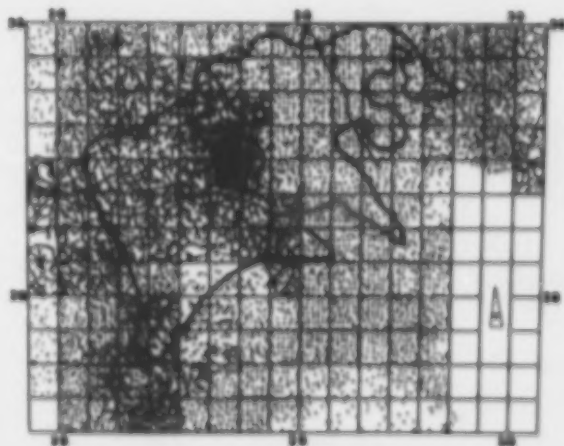


Figure 41.4. Gravity data coverage of the Witwatersrand Basin. A total of 13 500 stations make up the data set. The basin perimeter is shown for locational purposes.

itself. These data were colour plotted at scales of 1:500 000 and 1:250 000. In selecting a colour scale, the data were stretched in the mid-ranges so as to enhance low amplitude anomalies in regions of average background level.

- b) A 2000 m gaussian-smoothing operator was initially applied to the gravity data in order to reduce the effects of noise due to poor data leveling, still evident in the data set. Colour maps were also prepared at scales of 1:500 000 and 1:250 000. As with the magnetics, the data were stretched in the mid-ranges by judicious selection of a colour range so as to enhance low amplitude anomalies in regions of average background level.
- c) The above products were improved significantly when the potential-field software and computer facilities of the United States Geological Survey (USGS) in Denver were kindly made available to the senior author. All processing at the USGS was done on the preprocessed data sets rather than on the upward continued or gaussian smoothed data.

Colour-shaded relief maps were prepared of both the gravity and magnetic data at scales of 1:500 000 and 1:1 000 000 using an Applicon plotter. The maps essentially combine standard colour-coded versions of the stretched data, with shading of the magnetic relief determined by apparent sun elevation and azimuth. For the Witwatersrand data sets, a sun elevation of 30° was found to give an optimum effect and the maps were prepared at azimuths in 45° increments. The resultant data provided excellent visual products, retaining long wavelength features through suitable colour coding while simultaneously enhancing structural resolution through superimposition of the shaded relief. Noise was, of course, also enhanced and, in particular, flight-line leveling problems arose with one of the older aeromagnetic surveys. This did not detract from the overall enhancement of geological structure.

- d) Monochrome images of the two data sets were also prepared using the USGS facilities. Resolution was enhanced in two ways, firstly by a progressive linear stretch which effectively increases the grey-tone intensity of higher amplitude anomalies and, secondly, by edge enhancement of the stretched data. The products are presented as Photos 41.1 and 41.2.
- e) Finally, a procedure, implemented by the USGS, was employed to facilitate contact mapping with the aeromagnetic data. The procedure uses the principle that, with monopolar data, such as gravity data, the maximum slope of an anomaly lies close to the contact of a steeply dipping body. For this purpose the aeromagnetic data were transformed to pseudo-gravity data. The maximum slopes were identified by calculation of horizontal derivatives and the peak positions of the resultant anomalies were delineated using a program MAXSPOT (USGS unpublished program). Numerous contact positions were identified in this way thus removing some subjectivity from qualitative contact mapping. These transformations were applied assuming induced magnetization only, since the extent of resetting of the West Rand magnetization by the intrusion of the Bushveld Complex is unknown. Derived contact positions fitted well with borehole and outcrop information.

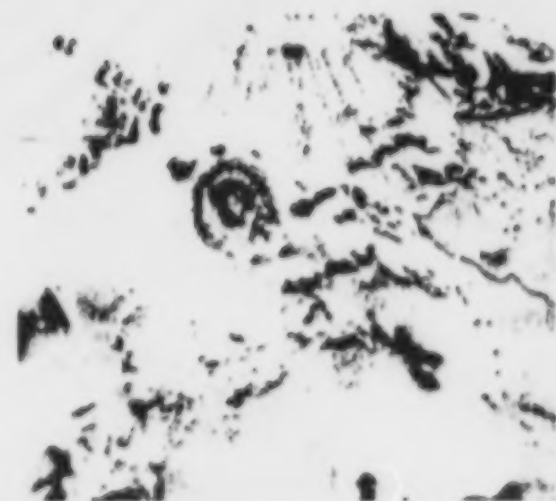


Photo 41.1. Image of the aeromagnetic data covering the Witwatersrand Basin (lighter shades represent positive anomalies; darker shades, negative anomalies).



Photo 41.2. Image of the Bouguer gravity data covering the Witwatersrand Basin.

tion of horizontal derivatives and the peak positions of the resultant anomalies were delineated using a program MAXSPOT (USGS unpublished program). Numerous contact positions were identified in this way thus removing some subjectivity from qualitative contact mapping. These transformations were applied assuming induced magnetization only, since the extent of resetting of the West Rand magnetization by the intrusion of the Bushveld Complex is unknown. Derived contact positions fitted well with borehole and outcrop information.

All the above products were utilized to remap the disposition of the West Rand Group, as well as

intrusions, dikes, faults, features in the basement, and structural lineaments. The colour maps could not be reproduced for this text and only the monochrome images (Photos 41.1 and 41.2) are presented here. They are nevertheless of high quality and show the majority of features seen on the colour shaded-relief maps.

QUANTITATIVE INTERPRETATION

Most methods for the automatic depth interpretation of magnetic profile data are limited by assuming only one or two simple geometric structures. A technique known as Euldep, which is not bound by this assumption, was developed by Thompson (1982). It is based on Euler's homogeneity equation for potential field data and relies on a structural index, describing the geometry of the source which best represents the anomaly. The structural index is a measure of the fall-off rate of the anomaly, or 'sharpness' of the anomaly relative to the depth (Thompson 1982). The Euldep method was considered to be preferable to other methods such as Werner deconvolution or the method of Naudy (1971) since it may be applied to a wide range of geological structures. This increased flexibility also allows more interaction by the interpreter who may decide between two or more depth solutions, based on geological knowledge of an area.

The technique was programmed at the University of the Witwatersrand by Durrheim (1985) for two-dimensional data. The program, EULDEP, was utilized by Wilsher (1987) to analyze all the magnetic data covering the basin. For this purpose, profiles were selected either in a north-south or an east-west direction every 5 km. A strike correction was applied where there was a significant deviation of the profile direction from orthogonality with geological strike. Wilsher (1987) discussed the validity of the depth solutions on the basis of comparison with geological data. Around the edge of the basin, the depth solutions are within 5 percent of those depths derived from boreholes located on the anomalies. Within the basin, depth solutions are often separated from borehole positions by several kilometres giving a variation between the calculated depths and drilling results of up to 30 percent. This figure is, however, not considered to be an error in view of the structural complexity of the area, and it is felt would be considerably less if direct comparisons could have been made.

Kilty (1983) extended the use of Werner deconvolution for depth analysis to gravity data and showed that exact depth estimates were not always possible with such data, although the analysis does provide information on the maximum depth to basement. It was decided to implement both the Werner deconvolution and Euldep methods for the interpretation of gravity data in this study. This was achieved by Wilsher (1987) by combining gravity and mag-

netic potentials through Poisson's Relation and modifying the Werner deconvolution and Euldep programs of Durrheim (1983, 1985). Wilsher (1987) conducted a detailed comparison of solutions, derived from the two methods, using theoretical gravity profiles from a variety of source geometries. She concluded that the Werner and Euldep based gravity programs pick out body edges accurately but the depth solutions are less accurate than the magnetic solutions.

Gravity profiles were selected at 25 km intervals in both north-south and east-west directions for depth calculations using both the Werner and Euldep gravity programs (Wilsher 1987). These profiles were analyzed in a similar way to the magnetic data. Wilsher (1987) discussed the validity of solutions with respect to the Witwatersrand Basin and has used the gravity solutions together with the aeromagnetic solutions (primarily) and borehole data to define depths to the West Rand Group throughout the area.

FORWARD MODELING

A number of profiles were selected for forward modeling so as to assist in the interpretation of the basin and underlying basement structure. The geological sections presented in Figures 41.5a and 41.5b are based on forward modeling of portions of the sections and are examined in the "Discussion" section.

The two-dimensional forward modeling was conducted using standard modeling programs for both gravity and magnetic data. The models were constrained using mapped contact positions, borehole data and measured physical properties (Table 41.1) where such data were available. Ambiguity was further reduced by the simultaneous modeling of both gravity and magnetic data for each profile.

COMBINED INTERPRETATION

All data sets were finally combined into a single unified interpretational map presented as Figure 41.6. In summary, the data sets which were used in the compilation include: the original mapping of Pretorius *et al.* (1986); borehole data provided by the Economic Geology Research Unit of the University of the Witwatersrand (D.A. Pretorius, University of the Witwatersrand, Johannesburg, personal communication, 1986); the results of geophysical mapping using the techniques described in the section on "Qualitative Interpretation"; and depth solutions derived from analysis of the magnetic and gravity data as described in the section on "Quantitative Interpretation".

The results of earlier interpretations, based on the techniques outlined in parts a) and b) of the "Qualitative Interpretation" section and in the "Quantitative Interpretation" section, have been presented and discussed by Wilsher (1987), and

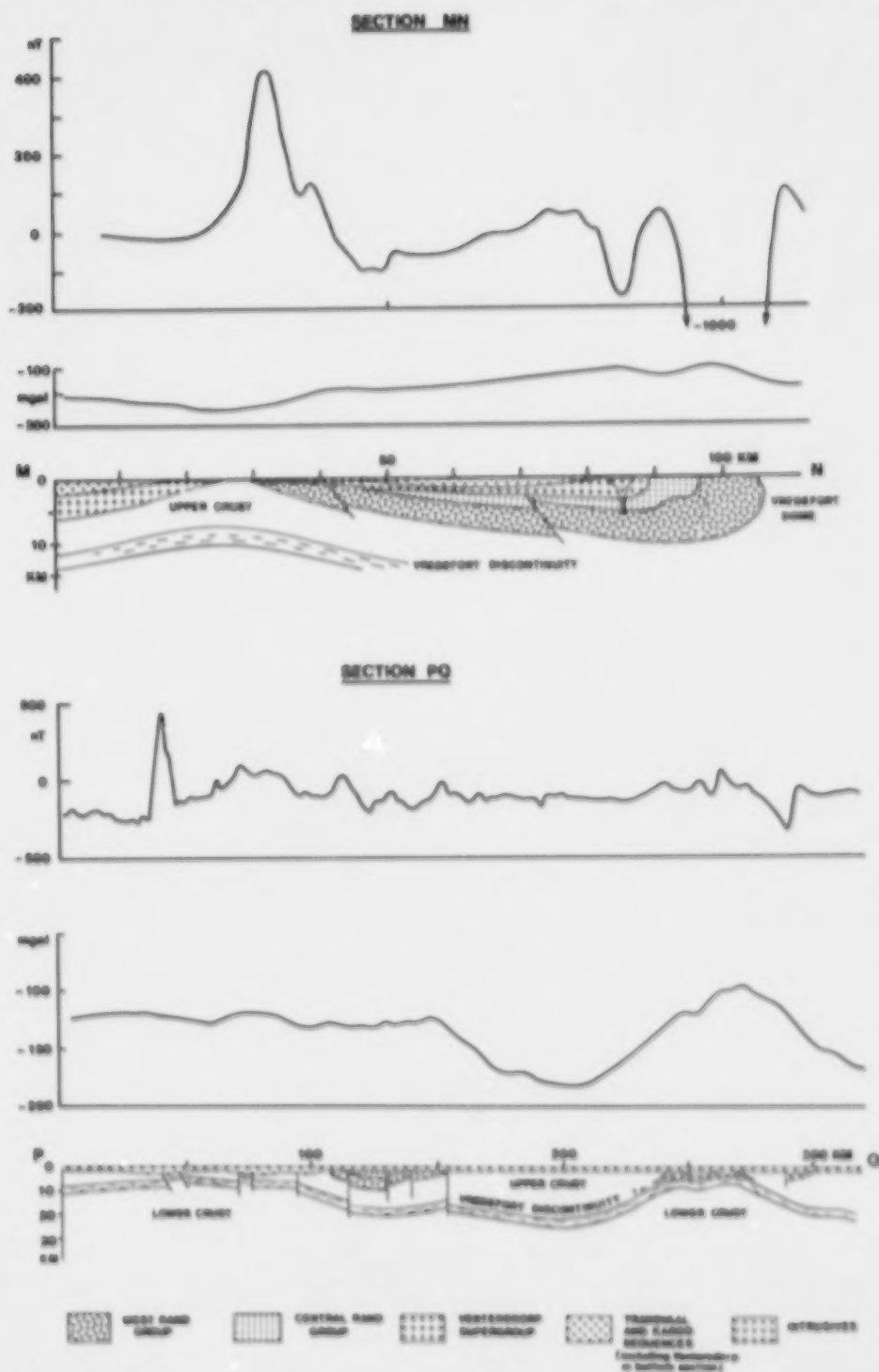


Figure 41.5. Geological sections traversing the Witwatersrand Basin, partially based on forward modeling of the gravity and magnetic data (for section locations see Figure 41.7). Figure 41.5a = section MN; Figure 41.5b = section PQ. Both sections show the observed magnetic (top profile) and Bouguer gravity (centre profile) above the derived geological section.

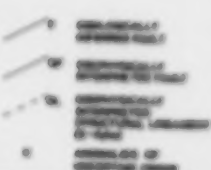


Figure 41.6. Interpretational map of the Witwatersrand Basin derived in this study.

Corner *et al.* (1986b). Figure 41.6 represents a synthesis of these, together with the most recent interpretation based on the techniques discussed in parts c), d), and e) of the "Qualitative Interpretation" section.

In a parallel study, Corner (1986a, 1987) mapped and interpreted regional cratonic structure using unprocessed aeromagnetic and Bouguer gravity data.

DISCUSSION

CRUSTAL STRUCTURE

An aspect which is highly significant to the study of the evolution of the Witwatersrand Basin is the identification of a magnetite-rich layer in the Archean crust, which has been used to map crustal structure associated with basin development and deformation. Figure 41.7, simplified after Corner *et al.* (1986a),

shows the basin in relation to the magnetically anomalous Archean basement. The latter is seen as a string of magnetic anomalies which parallels the perimeter of the basin to the west, south, and southeast at distances of between 100 and 150 km. These anomalies are collectively referred to as the Colesberg Trend. (Figure 41.7 is also used as a schematic magnetic anomaly index map so as to assist in the discussion of the more detailed map and images in Photos 41.1 and 41.2, and Figure 41.6).

In seeking an explanation for the Colesberg Trend, attention is focused on the core of the Vredefort Dome where an almost circular negative anomaly of high amplitude (1, Figure 41.7) arises from a magnetite-rich granitic layer. Accepting the crust-on-edge model for the dome (Hart *et al.* 1981), this layer is situated roughly 8 km below the base of the Witwatersrand Basin as exposed in the core of the dome. Hart and Andreoli (1986) reported detailed geochemical and isotopic studies

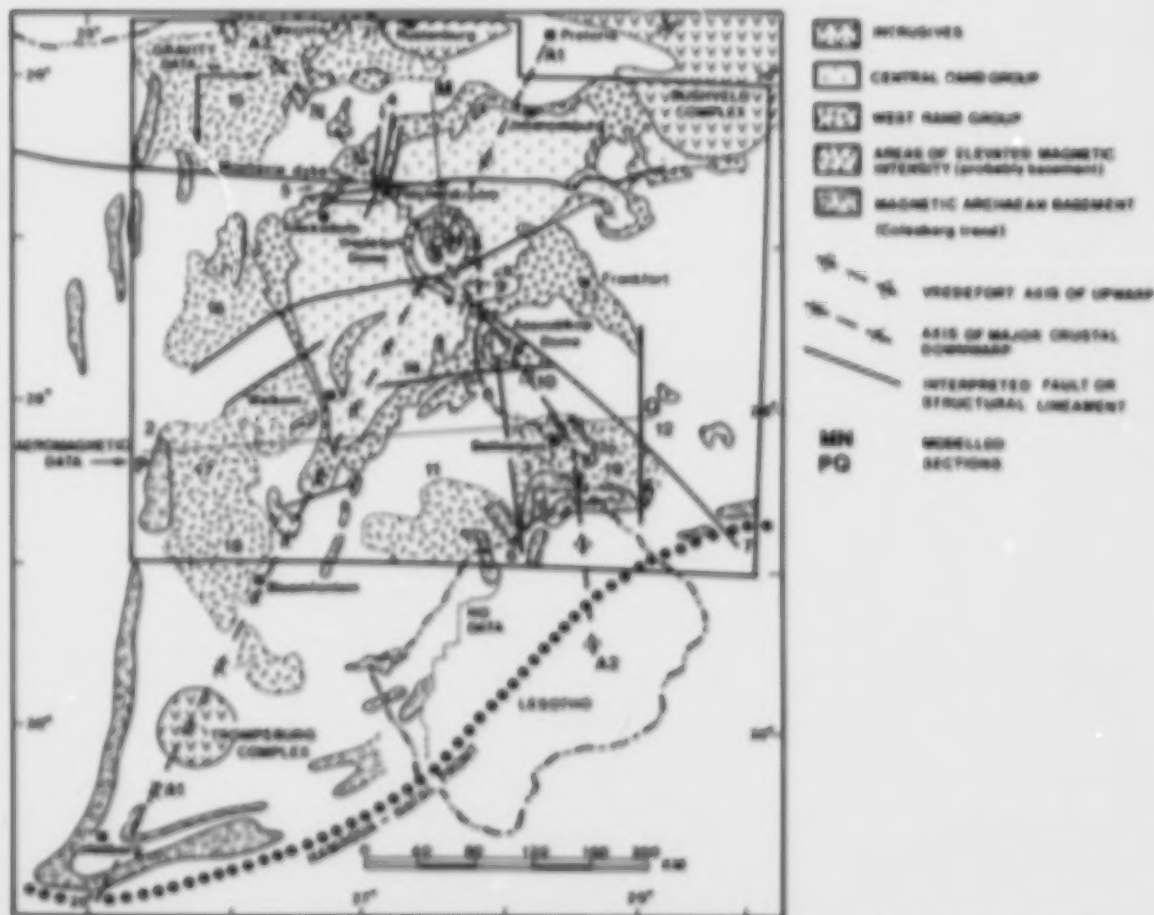


Figure 40.7. Simplified interpretational map of the southeastern portion of the Kaapvaal Craton (after Corner *et al.* 1986a). The numbers refer to features discussed in the text.

which show this layer to be a fundamental geochemical discontinuity separating upper from lower crust. They have termed this layer the Vredefort Discontinuity. Durrheim (1986) provided evidence from deep seismic reflection profiles that the Vredefort Discontinuity may also correlate, at depth beneath the Witwatersrand Basin, with a series of prominent reflectors.

Corner *et al.* (1986a) invoked a downwarp of the entire crust with dips between 4° and 8° directed towards the basin, bringing the Vredefort Discontinuity to the position of suboutcrop, beneath Phanerozoic cover, seen as the Colesberg Trend (Figures 41.7 and 41.5). This provides a working hypothesis for the parallelism between this trend and the perimeter of the basin. Corner (1987) interpreted the northward-trending string of anomalies (from Colesberg northward) to result from a faulted, low-angle arch, whereas the northeasterly and easterly trending branches represent a termination of the discontinuity against the Namaqua-Natal Front.

The high amplitude anomalies of the Colesberg Trend, arising from faulted boundaries of the Vredefort Discontinuity can be seen on the aeromagnetic image (Photo 41.1) with reference to Figure 41.7 (locations 1: negative anomaly; 2 and 3: positive anomalies). The change in sign of the anomalies arises from a resetting of the magnetization within the Vredefort Dome at the time of intrusion of the Bushveld Complex (Jackson 1982).

The geophysical manifestation of the Vredefort Discontinuity is interpreted to result both from a preferential enrichment of magnetite, and from mafic material arising from sill injection in, or ancient crustal underplating of, present-day intermediate to lower crust.

From the trend of the Vredefort Discontinuity and its relationship to the Witwatersrand Basin, a clear axis of symmetry, trending north-northeastward (A1, Figure 41.7) is evident. This axis also constitutes the long axis of the basin and represents a fundamental axis of early downwarp of the crust. The downwarp is thought to result from early extensional tectonics which initiated and accompanied Witwatersrand sedimentation. The axis also correlates with a younger, well known lineament of tectonic activity along which the Great Dyke of Zimbabwe, the axis of symmetry of the Bushveld Complex, the Johannesburg Dome, the Vredefort Dome, and the Trompsburg Complex are all situated.

The long wavelength magnetic highs situated broadly at locations 15, 16, 17, 18, and 19 (Photo 41.1, Figures 41.6 and 41.7) are thought to be due to large scale crenulations in the crust bringing the Vredefort Discontinuity closer to the surface. This is verified in the area west of Welkom by forward modeling (Figure 41.5b). The concept of crenulations in the crust supports, in part, the proposal of Pretorius (1986) that the Witwatersrand Basin and

environs has been controlled by a series of intersecting synclinal and anticlinal axes. The two sections partially based on forward-modeling (Figures 41.5a and 41.5b) provide an insight into some of the larger structural features which we have described. An important aspect arising from the forward modeling has been the recognition that cognisance must be taken of density and susceptibility variations in the crust as a whole in such modeling.

CRUSTAL STRUCTURE: THE VREDEFORT AXIS

A number of features interpreted from the magnetic and gravity data support the presence of a major geanticline (A2, Figure 41.7) trending northwestward from northern Lesotho and intersecting the older axis of crustal downwarp (A1, Figure 41.7) in the Vredefort Dome. The axis of this geanticline is termed the Vredefort Axis (Corner 1987). These features include:

- a) Conjugate fault lineaments on the northwestern and southeastern margins of the basin, reflecting a response to upwarping of the thick sedimentary pile where it thins out at the basin margins. The fault lineaments may be seen on the aeromagnetic image (Photo 41.1) by comparison with Figures 41.6 and 41.7: in the northwest, trending northward from Potchefstroom are a series of faults (4, Figure 41.7) which are readily seen in the magnetic data and which have been mapped geologically, e.g. the Potchefstroom, Turfontein, and Kromdraai Faults. Conjugate to these are a series of east-west faults passing through Potchefstroom which are delineated by dikes (5, Figure 41.7), presumably of a younger age, which have taken advantage of this older line of weakness. In particular, the Machavie Dike has been noted by Corner *et al.* (1986a) to correlate with a series of Archean faults and intrusions along its entire length of some 600 km. The east-west fault-lineament has not been mapped geologically, except along the Sugarbush Fault, and it is possible that it manifests itself as a rapid thickening of Central Rand sedimentation southward in response to an older fault margin.

A similar geometry is seen on the southeastern margin of the basin to the southeast of Vredefort, i.e. fault lineaments 6 and 7 (Figure 41.7) interpreted from the aeromagnetic data (Photo 41.1). The Vredefort Dome occurs in the northwestern sector of this conjugate set and the Aasvoëlkop Dome in the southeastern sector. The latter dome is identified and named for the first time in this combined study (Corner *et al.* 1986a). The collar rocks, which correlate with a low order gravity high encircling a gravity low (8, Figure 41.7), are interpreted as belonging to the West Rand Group.

- b) The Vredefort Dome itself is seen as part of the manifestation of the northwest-trending geanticline. It is situated on the intersection of the

older axis of crustal downwarp and the Vredefort Axis. Mechanically this would be the most disturbed portion of the crust and it is possible that this provided the pathway of rapid devolatilisation of the mantle and diapirism, forming the prominent dome which is seen today.

A gravity low (9, Photo 41.2 and Figure 41.7) links the Vredefort and Aasvoëlkop Domes, signifying an opening of the Vredefort Dome to the southeast. This low constitutes the Vredefort Axis in this region.

- c) The Bethlehem gravity high (10, Photo 41.2 and Figure 41.7) is one of the most prominent gravity highs on the Kaapvaal Craton when compared to the low Bouguer gravity anomalies occurring to the southwest (11, Figure 41.7) and east (12, Figure 41.7). It is interpreted in terms of the geantlinal model proposed here, i.e. an extension of the Vredefort Axis southeastward, which has brought lower crust close to surface, possibly suboutcropping under the Phanerozoic Karoo sediments in the area. This model was put to the test by forward modeling of both the gravity and magnetic data. Good agreement was found between observed and theoretically calculated fields.

The interpretation, therefore, is that prominent crustal upwarping along the Vredefort Axis southeast of the basin has brought denser, intermediate, and lower crust, and associated mafic units nearer the surface in the vicinity of Bethlehem. This feature, however, plunges northwestwards along the Vredefort Axis, such that where it deepens under the basin, less dense upper crust situated above it gives rise to the gravity low (9) linking the Aasvoëlkop and Vredefort Domes. The intermediate crustal rocks appear again at surface in the centre of the Vredefort Dome as modeled by Stepto (1979).

- d) Finally, the abrupt change in direction of the magnetic anomalies of the Vredefort Discontinuity from northeastward along the western Lesotho border to due east near Bethlehem (3, Photo 41.1 and Figure 41.7), is also interpreted as resulting from crustal upwarping along the Vredefort Axis. That is, one would expect the observed change in strike direction of the magnetic anomalies (3), to originate from the Vredefort Discontinuity being upwarped about the Vredefort Axis, and eroded in pre-Karoo times.

It should be noted that the Vredefort Axis was recognised by earlier workers. Stepto (1979) identified it as an axis within the Vredefort Dome about which both geological structure and the gravity field were uniquely symmetrical. Pretorius (1976) identified the Vredefort Axis as the Koppies Anticline and pointed out the symmetry of the basin about this axis. This general symmetry is clearly seen in Photo

41.1 and Figure 41.6. Notable exceptions to this symmetry are at least three major subsidiary basins to the northeast of the Vredefort Axis, i.e. the Frankfort, South Rand, and Evander Basins, which have no counterpart to the southwest of the axis.

INTERPRETATIONAL MAP OF THE WITWATERSRAND BASIN

The detailed interpretational map in Figure 41.6 differs significantly from the most recently published geological map of the basin (Pretorius *et al.* 1986) in the following respects:

- a) The prominent set of magnetic anomalies and corresponding gravity high trending southeastward through Frankfort (13, Photos 41.1 and 41.2, Figures 41.6, and 41.7) are interpreted as originating from a major trough subsidiary to the main basin. This is termed the Frankfort Basin. Knupp (1987) has shown, through forward modeling of the gravity and magnetic data, that a 7 km thick sedimentary pile, with densities and susceptibilities similar to the West Rand Group, is needed to satisfy the observed data. The presence of Central Rand Group sediments cannot, however, be unambiguously modeled with the existing data sets.
- b) The Aasvoëlkop Dome is also a newly identified feature.
- c) Structural detail in the West Rand Group rocks and basement, west, and south of Welkom, has been greatly enhanced.
- d) The presence of West Rand Group rocks at depth has been identified by a deep borehole drilled by the Geological Survey of South Africa into the magnetic anomaly at Mazista, west of Rustenburg. Current mapping has, through correlation with this borehole, indicated a far more extensive development of West Rand Group rocks in the area, constituting a further sub-basin to the north.
- e) Structural detail has in general been greatly enhanced in terms of the mapping of faults and fault lineaments. An excellent example is the right-lateral fault mapped south of the Vredefort Dome (14, Photo 41.1, Figures 41.6 and 41.7).
- f) The correlation of small magnetic sources outside the main basin with outliers of West Rand Group rocks is tentative and open to confirmation as they have not been verified by publicly available borehole data. Similarly, magnetic units identified as features within the basement may correspond to West Rand Group relicts or mafic intrusions.
- g) Significant changes in the depth-to-base isodepth contours of the Central Rand Group have been made as a result of the additional geophysically derived depths.

CONCLUSIONS

Rigorous interpretation of aeromagnetic and gravity data has enabled the compilation to be made of a detailed subsurface map of the Witwatersrand Basin. This was achieved through the application of image processing techniques, forward modeling and the inversion of the data to yield depths to anomalous sources, coupled with published geology and drilling results. The interpretational map represents a significant improvement over previous mapping. A major subsidiary basin, the Frankfort Basin, has been identified and mapped and a major deep-seated outlier of West Rand Group rocks has been delineated to the northwest of the main basin. The Aasvoëlkop Dome, conjugate to the Vredefort Dome, although smaller, has been identified and delineated for the first time.

Regional structural mapping has been upgraded with the addition of numerous faults, fault lineaments, and structural grain. Published isodepth contours to the base of the Central Rand Group have been modified on the basis of geophysically calculated depths.

Regional mapping of the aeromagnetic data outside the basin has identified a magnetite-rich, granitic layer in the crust which is correlated with a similar feature in the core of the Vredefort Dome — the Vredefort Discontinuity. This feature has facilitated the identification of a major crustal downwarp about a north-northeast-trending axis which is interpreted as having either responded to the weight of Witwatersrand sediments or initiated the sedimentation. A younger axis (the Vredefort Axis) of crustal upwarp is interpreted from the data, and cuts the axis of downwarp symmetrically through the centre of the basin intersecting it in the Vredefort Dome. Both axes are considered to be highly significant in controlling the evolution and structure of the basin.

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42. Exploration Geophysics for Athabasca Uranium Deposits

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ABSTRACT

This paper presents results of geophysical surveys used in exploration for uranium deposits of northern Saskatchewan associated with the unconformity between the Helikian Athabasca sandstone basin and an older crystalline basement. The physical properties of the geologic model for a typical deposit is presented. Examples from the Key Lake, Dawn Lake, Cigar Lake, and Cree Extension projects illustrate the optimum geophysical exploration approach to locate unconformity-type mineralization at depths as great as 600 m.

Although direct radiometric methods have had some success in the past, the search is now for blind deposits using indirect methods. In view of the association between non-magnetic basement graphitic metasediments and uranium mineralization, airborne electromagnetic and magnetic techniques are the primary reconnaissance tools, followed by ground EM to delineate the graphitic horizons prior to diamond drilling. The EM techniques are supplemented by potential field and resistivity methods to map basement geology, and to delineate faulting and hydrothermal alteration zones.

INTRODUCTION

Uranium exploration has a long history in Saskatchewan (Langford 1985), pitchblende having been noted first by F.J. Alcock of the Geological Survey of Canada in 1936, on the north shore of Lake Athabasca. This area developed in the late 1940s and 1950s, to become the Beaverlodge mining camp. The peak uranium mining activity occurred in 1958, when sixteen mines were operating in the Uranium City area. The industry slowed down in 1959 due to general oversupply.

Exploration outside of the Beaverlodge area was initiated in 1964 within the Athabasca Basin by Compagnie de Mokta Limitée. Airborne scintillometer surveys outlined anomalous radioactivity in the Fond du Lac, Stony Rapids, and Carswell Lake areas. Ground follow-up (prospecting and drilling) in the latter area led to the discovery of the D deposit in 1969.

Other airborne radiometric surveys along the eastern margin of the Athabasca Basin were carried out by a consortium of Calgary oil companies. The Rabbit Lake Deposit was discovered in 1968 by Gulf Oil Canada. This deposit indicated a connection between the Athabasca Group sandstone and uranium mineralization. After the ensuing staking rush, most of the Athabasca Basin was held in mineral dispositions.

In 1975 and 1976, the exploration partnership of Uranerz Exploration and Mining Limited and Saskatchewan Mining Development Corporation discovered the Gaertner and Deilmann orebodies at Key Lake. The Key Lake deposits are significant because this is where the relationship between uranium mineralization and basement graphitic metasediments was first recognized. Since that time, geophysical exploration in the region has largely become a search for associated graphite using electromagnetic methods.

Geophysics has played a major role in the history of uranium exploration in Saskatchewan. As a better understanding of the geologic setting of unconformity-related deposits evolved over the last decade, the application of geophysics has become quite sophisticated. This paper discusses the geophysical model used to guide exploration in the Athabasca Basin. The model is illustrated by examples of geophysical methods from four uranium exploration projects, which cover the depth range of 50 m to more than 600 m to the sub-Athabasca unconformity. In conclusion, the optimum exploration approach to finding conventional unconformity-related mineralization using geophysical techniques is presented.

REGIONAL GEOLOGY

The Athabasca Basin of northern Saskatchewan covers more than 100 000 km², and has been the focus of most of the uranium exploration in Saskatchewan since the late 1970s (Figure 42.1). The Athabasca is a Helikian basin of cleanly washed sandstones and conglomerates, which has been subdivided into three northeast-trending sub-basins; the Jackfish in the northwest, the Mirror in the central region, and the Cree in the east. The sediments



Figure 42.1. Regional Geology: Northern Saskatchewan regional geology showing the locations of uranium mines and major deposits.

filling these basins form the Athabasca Group (Ramaekers 1983). The Manitou Falls Formation in the eastern part of the basin hosts most of the major uranium deposits. This formation is composed of orthoquartzite sandstones and conglomerates.

The underlying crystalline basement rocks are Archean supracrustals of the Wollaston Group, which are draped over interpreted Archean granitic gneiss domes. The Wollaston Group is subdivided into a lower graphitic, pelitic metasedimentary unit, overlain by dominantly meta-arkose and meta-quartzite units. The basement rocks under the eastern Athabasca Basin have been subdivided into two lithostructural domains. The Wollaston Domain is characterized by a strongly folded linear belt, in contrast to the Mudjatik Domain to the west, which has a generally rectilinear pattern (Sibbald 1983) possibly caused by block faulting or interference folding. Metamorphism in the Wollaston Domain reached upper amphibolite facies. The metamorphic grade in the Mudjatik Domain may have been somewhat higher, reaching the granulite facies.

The majority of the occurrences of uranium mineralization are located in the western Wollaston

Domain, adjacent to the Mudjatik Domain boundary. The deposits apparently are in part controlled by the basement stratigraphy, and are associated with basal graphitic metapelites close to domes of Archean granite gneisses. Mineralization is related to the sub-Athabasca unconformity, and is controlled by basement and sandstone faulting. The four study areas are Key Lake, Dawn Lake, Cigar Lake, and Cree Extension, all of which are located in the western Wollaston Domain (see Figure 42.1).

REGIONAL GEOPHYSICS

Regional total field magnetic surveys are the most effective method of mapping the sub-Athabasca basement geology. The Athabasca Group sandstones have undergone a pervasive diagenetic alteration which has destroyed most of the original magnetic minerals. The Athabasca Group rocks are therefore magnetically transparent. The pelitic metasedimentary rocks of the Wollaston Group are typically weakly magnetic, whereas the Archean granitic gneisses have a relatively stronger magnetic signature. Upper Archean arkoses and quartzites in the eastern Wollaston Domain have a very strong magnetic signature.

The regional magnetic pattern of northern Saskatchewan is shown in Plate 42.1 (see Colour Folio near back of book). The western Wollaston Domain is evident as a linear belt of generally low magnetic signature, caused by the predominance of Archean metasediments. The eastern Wollaston is dominated by strongly magnetic arkoses and quartzites. More magnetic rocks dominate in the adjacent Mudjatik Domain.

Few density measurements of sub-Athabasca basement rocks are available to aid in the interpretation of gravity surveys. Pelitic metasediments have a generally higher density than the Archean granitic gneisses. Regional gravity surveys in northern Saskatchewan were undertaken in 1960 and 1965 by the Earth Physics Branch of the Department of Energy, Mines and Resources. The contours of Bouguer gravity of northern Saskatchewan parallel the general northeast trend of the basement rocks. The sample density of the gravity readings is too coarse to map basement lithology except on a regional scale.

GEOPHYSICAL MODEL

The typical unconformity-related uranium deposit, as depicted in Figure 42.2, has the following geologic characteristics: mineralization at or near the sub-Athabasca unconformity, directly associated with graphitic metasedimentary basement rocks, and in part controlled by basement faulting. The geophysical signature is primarily that of a discrete basement graphitic EM conductor within a broader zone of low resistivity indicating a hydrothermal alteration envelope. The alteration zone may also be detect-

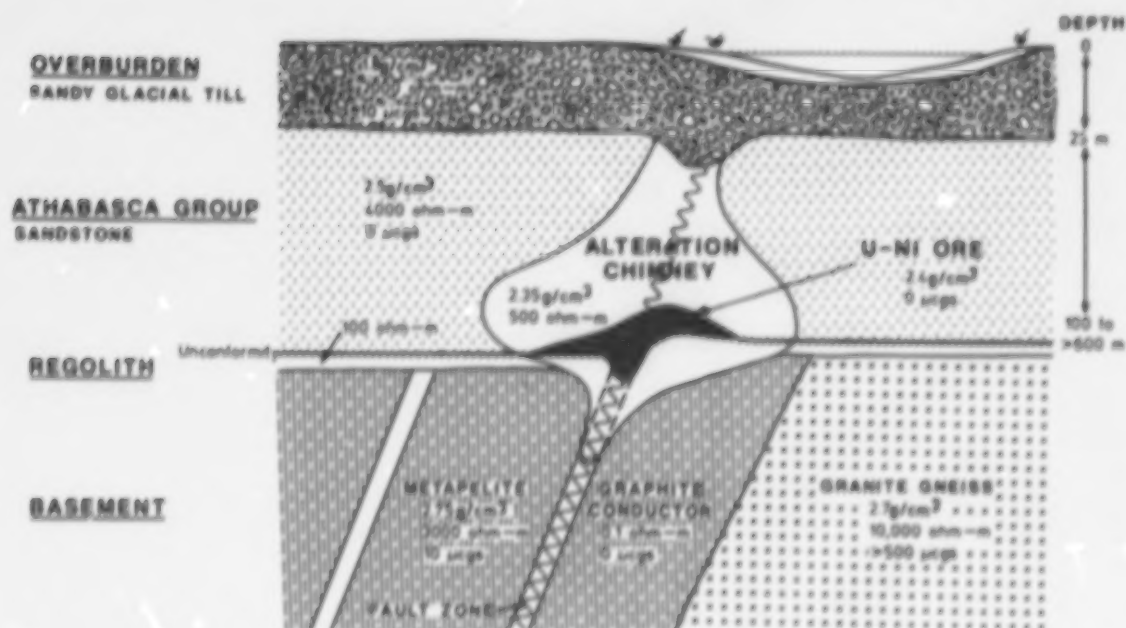


Figure 42.2. Geophysical Model: Geophysical model for a typical unconformity-related uranium deposit showing the range of rock physical properties. The geophysical signature is primarily that of a basement graphitic EM conductor within a low resistivity hydrothermal alteration envelope.

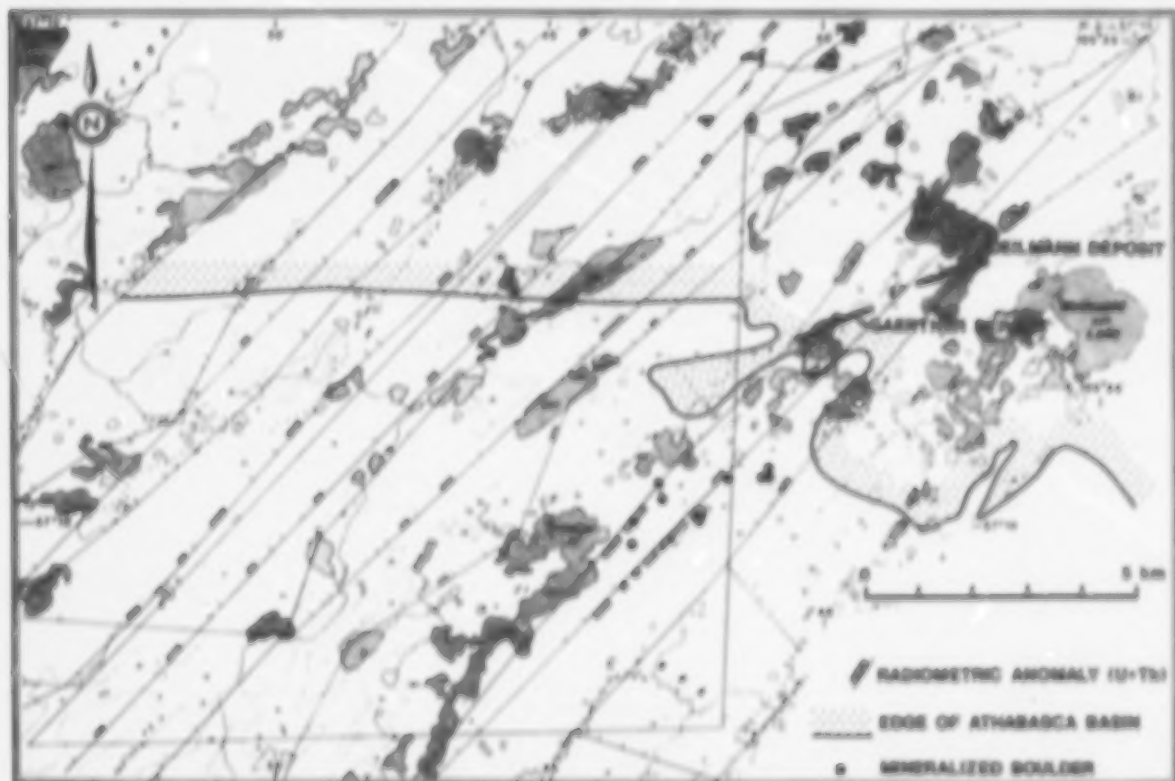


Figure 42.3. Key Lake Airborne Radiometrics: Airborne spectrometer survey over the Key Lake area. Radiometric anomalies more than two times background were located southwest of the Gaertner and Deilmann orebodies.

able as a local gravity low. Regionally the favourable basement metasediments are seen as magnetic lows and gravity highs. The most prominent geophysical characteristic would be a radioactive boulder train, but this only occurs where the deposit has been exposed to glacial erosion.

The values for magnetic susceptibility, density, and resistivity/conductivity given on the model represent ranges taken from several hundred measurements on drill core samples. These values may not be strictly valid for use in a regional interpretation, because most of the samples have been taken from the vicinity of the deposits, and may be strongly affected by local alteration.

KEY LAKE PROJECT

The Key Lake deposits are located at the southwestern edge of the Athabasca Basin, in the western Wollaston Domain (see Plate 42.1). Mineralization in the Gaertner and Deilmann deposits is hosted by a northeast-trending basement fault zone, at the sub-Athabasca unconformity. The basement rocks underlying the deposits are Archean graphitic pelitic metasediments. The area is completely covered with an average of 20 m of sandy glacial till and outwash sand.

The examples of geophysical surveys presented here traverse the Gaertner deposit which has a 1400 m strike length, with a maximum thickness of 80 m, and a minimum depth of 40 m to the sub-Athabasca unconformity (Ruhmann 1987). The mineralization is mostly within the Athabasca Group sandstone. Geologic reserves of the combined Gaertner and Deilmann orebodies are estimated at 188.4 million pounds of uranium at an average grade of 2.5 percent U_3O_8 .

The regional geophysical setting of the Key Lake deposits is shown in Plate 42.2. The orebodies are situated in a broad magnetic low, indicative of pelitic metasedimentary basement rocks, on the flank of a magnetic high outlining an Archean granite gneiss dome. Strong EM conductors detected by the Mark VI INPUT® airborne EM system flown by Questor Surveys Limited are caused by graphitic horizons within the metasediments, which wrap around the central granite gneiss core. The significant basement fault zone which hosts the orebodies is not seen in the magnetic contours because it is sub-parallel to the stratigraphy.

The airborne radiometric method was the first geophysical technique applied in 1969. Radiometric anomalies, more than twice background levels in the uranium energy window, were located northeast of Zimmer Lake (Figure 42.3). Ground prospecting confirmed the source of the airborne anomalies as radioactive swamps and boulders of massive ura-

nium-nickel ore. The mineralized boulder train was eventually traced 5 km to the northeast to its source near Key Lake. The deposits have been eroded by glaciation, which accounts for the presence of mineralized boulders at surface.

In the early 1970s the association of uranium mineralization with graphitic metasediments was not recognized, but because of the high base-metal content (primarily nickel arsenides) of the mineralized boulders, ground EM was used in the Key Lake area to provide targets for diamond drilling. Horizontal loop EM (Figure 42.4) traced a strong conductor over several kilometres strike length. Conductivity-width and depth estimates from the horizontal loop EM (HLEM) profiles are inaccurate due to phase rotation caused by conductive host rock. Because of

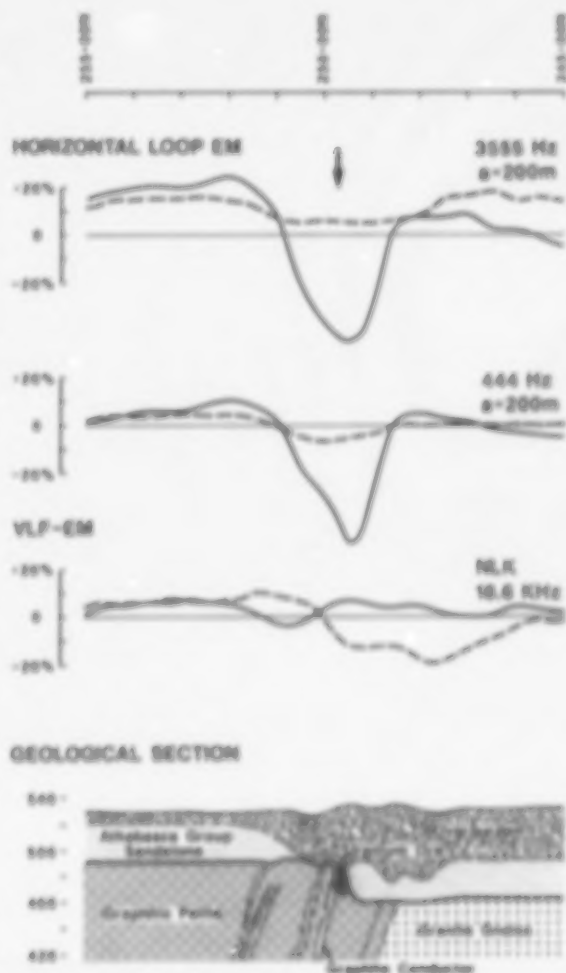


Figure 42.4. Key Lake EM Profiles: Horizontal Loop EM and VLF-EM profiles from Line 162+00E over the Gaertner Deposit. Note the direct correlation of the EM conductor axis with the uranium mineralization shown on the geologic section.

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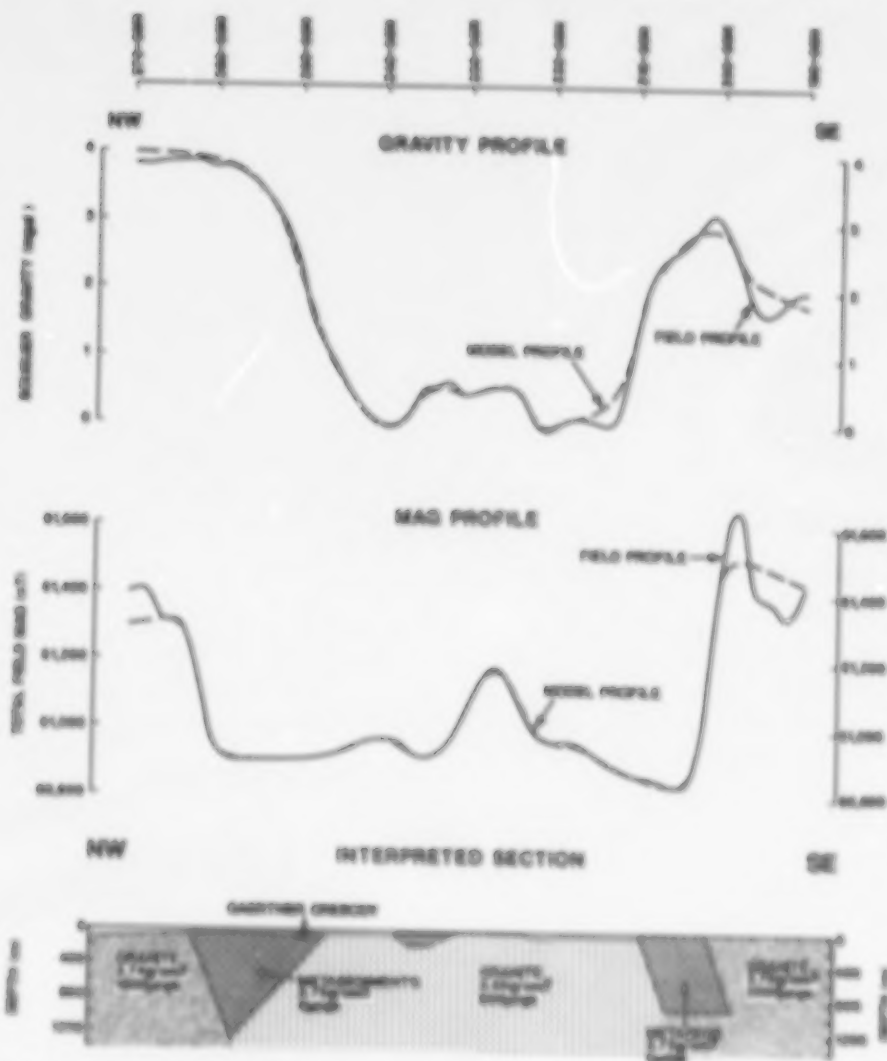


Figure 42.5. Key Lake Regional Gravity: Bouguer gravity and total field magnetic profiles from Line 166x00E over the Key Lake dome. The interpreted section and model profiles show the low density, high magnetic signature of the Archean granite in contrast to the Proterozoic metasediments.

the shallow sandstone cover, VLF-EM (see Figure 42.4) is also effective in mapping basement conductors. The interpreted EM conductor axis correlates directly with the uranium mineralization in the geologic section presented in Figure 42.4.

Regional gravity coverage across the Key Lake deposits (Figure 42.5) shows a well-developed gravity low of 4 mgal over the granite gneiss dome. The total field magnetic profile is slightly elevated over the dome. Interpreted granite units further to the northwest and southeast are expressed as intense magnetic highs with minor gravity signatures. Computer modelling of the gravity and magnetic re-

sponses confirms that the metasediments are draped over a granite gneiss core. This example illustrates the complementary capabilities of gravity and magnetism in mapping the basement stratigraphy.

Detailed gravity (Figure 42.6) shows the signature of the Gaertner orebody as a minor 0.3 mgal low, which is superimposed on the larger response from the density contrast between the metasediments and granite gneiss. The uranium-nickel ore can be locally quite dense (up to 12 g/cm³), but has a small volume. The gravity low over the deposit is caused by the much larger low density hydrothermal alteration envelope.

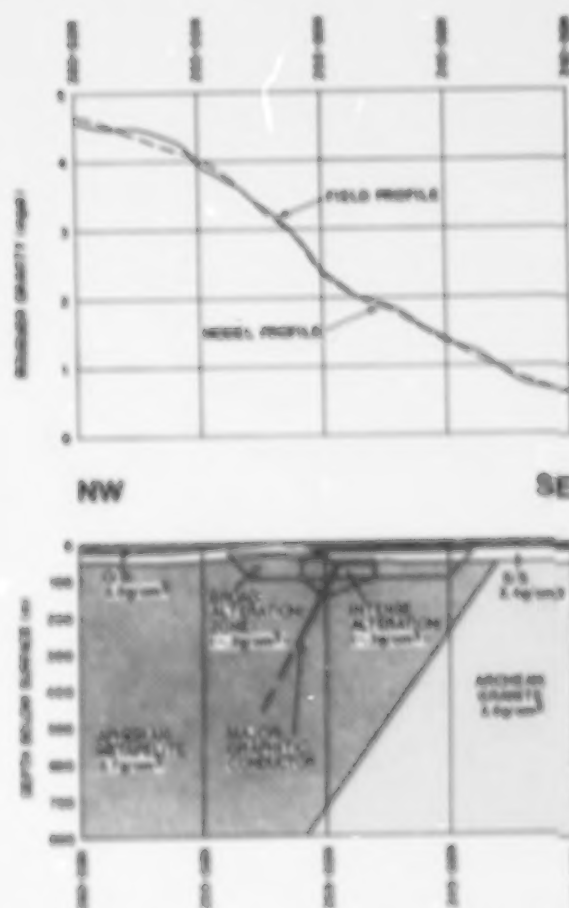


Figure 43.6. Key Lake Detailed Gravity: Bouguer gravity profile from Line 164+00E over the Garson deposit. Gravity modelling shows the low density alteration envelope more than compensates for the high density ore.

DAWN LAKE PROJECT

The Dawn Lake deposits are among the few blind deposits in the Athabasca Basin, that is, the deposits do not have an associated radioactive boulder train. Asamera Oil Corporation Limited discovered mineralization in the 11, 14, 11A, and 11B Zones, by diamond drilling a Turam conductor (Clarke and Fogwill 1985). The Turam method was used to follow up an INPUT anomaly.

Geologic reserves of the Dawn Lake deposits are 10 million pounds at 1.97 percent U_3O_8 . In this area the depth to the sub-Athabasca unconformity is approximately 110 m, and mineralization in the four zones is associated with two subparallel graphic conductors hosted in pelitic metasediments.

The regional geophysical setting is shown in Plate 42.3 (see Colour Plate near back of book).

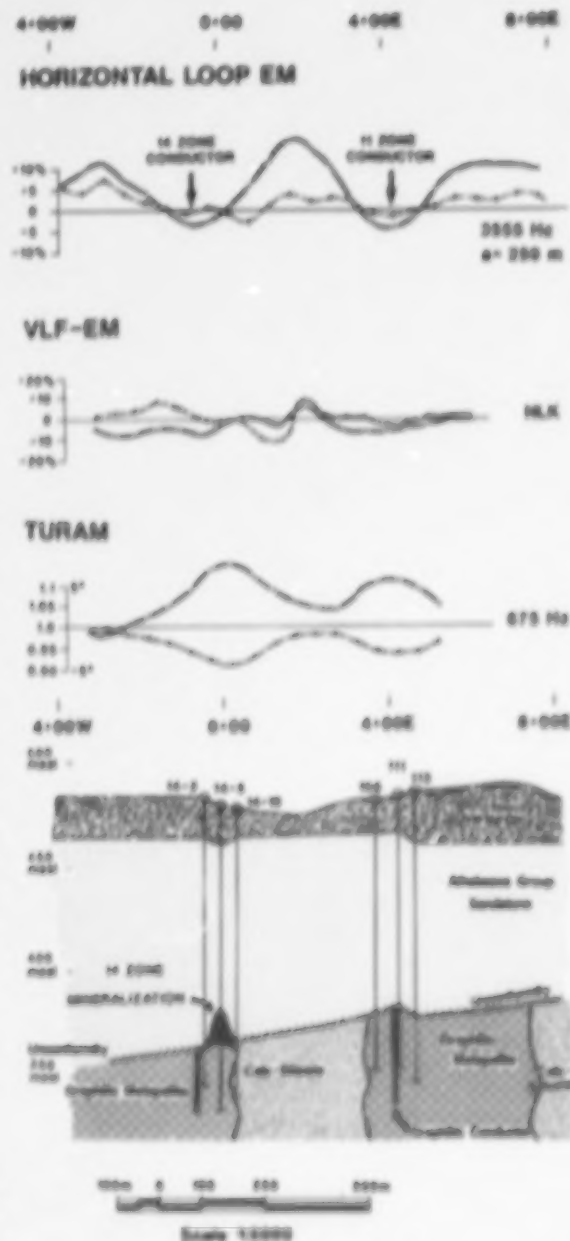


Figure 43.7. Dawn Lake EM Profiles: Horizontal Loop EM, VLF-EM, and TURAM EM profiles from line 51+00N over the 11 and 14 Zone conductors. Only the 14 Zone conductor is mineralized in this section.

Dawn Lake is located within a broad magnetic low, interpreted to represent a thick sequence of Achean mixed metasediments (pelites to calc-silicates). Strong multiple INPUT conductors extend for several kilometres in a northeasterly direction. There is no evidence that the metasediments are wrapped around a central granite gneiss core, as at

Key Lake, which suggests that the Dawn Lake deposits are possibly higher up in the Wollaston Group stratigraphy. The faulting which controls the mineralization is subparallel to the basement stratigraphy, and is therefore not evident in the magnetic contours.

Many different types of ground EM surveys have been conducted over the Dawn Lake deposits. Horizontal loop EM (Figure 42.7) results in strong responses from both the 11 and 14 Zone conductors. There is some evidence of phase rotation at the higher frequencies, caused by conductive host rock, which is possibly indicative of alteration in the sandstone.

Both conductors also respond well to Turam (see Figure 42.7), which was the method used to locate the conductors in the original discovery. The EM profiles cross both the 11 and 14 Zone conductors. Only the 14 Zone conductor is mineralized in this section, but there does not appear to be any difference in the EM response compared to the 11 Zone conductor.

To cover the large mineral dispositions which are common in uranium exploration in Saskatchewan, airborne EM is the method of choice. The INPUT system has proved the most effective in mapping basement conductors up to hundreds of metres depth. INPUT (Induced Pulse Transient) measures the earth response in six time channels after shut off of a half sine wave primary pulse. The 11 and 14 Zone conductors are strong 3 and 4 channel INPUT responses (Figure 42.8), with channel 1 peak amplitudes up to 100 ppm. Note that there are other weaker responses other than the 11 and 14 Zone conductors evident in this profile.

A new development in time domain airborne EM systems is the Geotrex GEOTEM[®] (Thomson 1987). GEOTEM uses the conventional INPUT transmitter, but has a more sophisticated digital receiver. The digital receiver is inherently more flexible than the analogue INPUT receiver, and provides programmable time gates. The time gates can be shifted to better sample the ground response of different geological environments.

GEOTEM profiles in Figure 42.9 cover the same section across the Dawn Lake deposits as the INPUT profiles of Figure 42.8. The twelve channels of GEOTEM have been programmed in a pseudo-binary progression through the transmitter off-time. GEOTEM channel 4 is approximately equivalent to INPUT channel 1. The response amplitudes are similar, but the lateral resolution of the 11 and 14-Zone conductors with GEOTEM is much improved, and the noise levels, particularly in late time channels, are reduced. The weak conductors noted

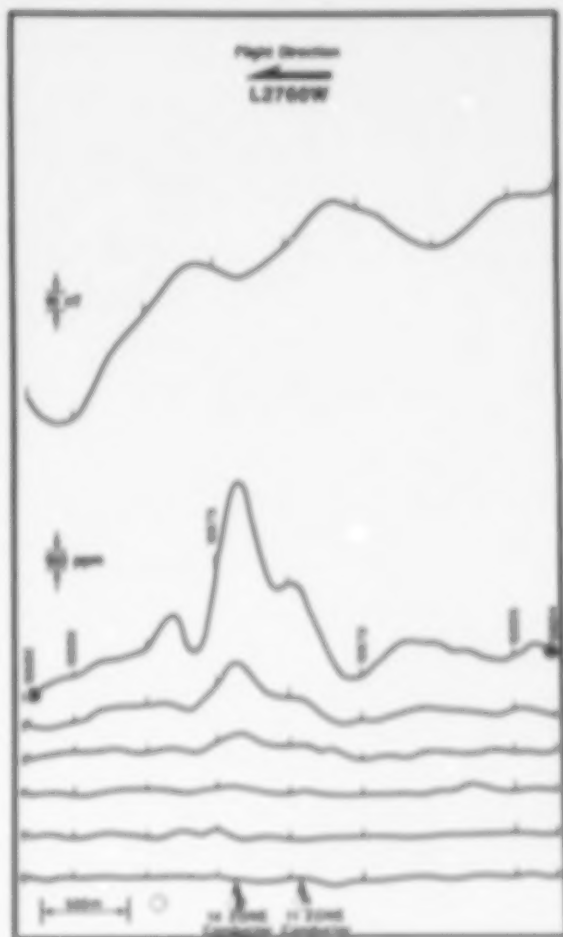


Figure 42.8. Dawn Lake INPUT Profiles: INPUT EM profiles over the 11 and 14 Zone conductors show strong 3 and 4 channel responses.

in the INPUT profile have a larger response with the GEOTEM system due to the earlier time channels.

CIGAR LAKE PROJECT

The Cigar Lake deposit is the largest orebody in the Athabasca Basin, and possibly the world. The geologic reserves of the Main Pod are estimated at 285 million pounds at 14.4 percent U_3O_8 , and for the western extension at 100 million pounds at 4.8 percent U_3O_8 . The orebody was discovered in 1981 by Cogema Canada Limited, operator of the Waterbury Lake Joint Venture.

The Cigar Lake orebody is located at the sub-Athabasca unconformity, at a depth of approximately 450 m. The basement rocks under the deposit are Archean graphitic metasediments of the Wollaston Group (Brunson 1984). The orebody

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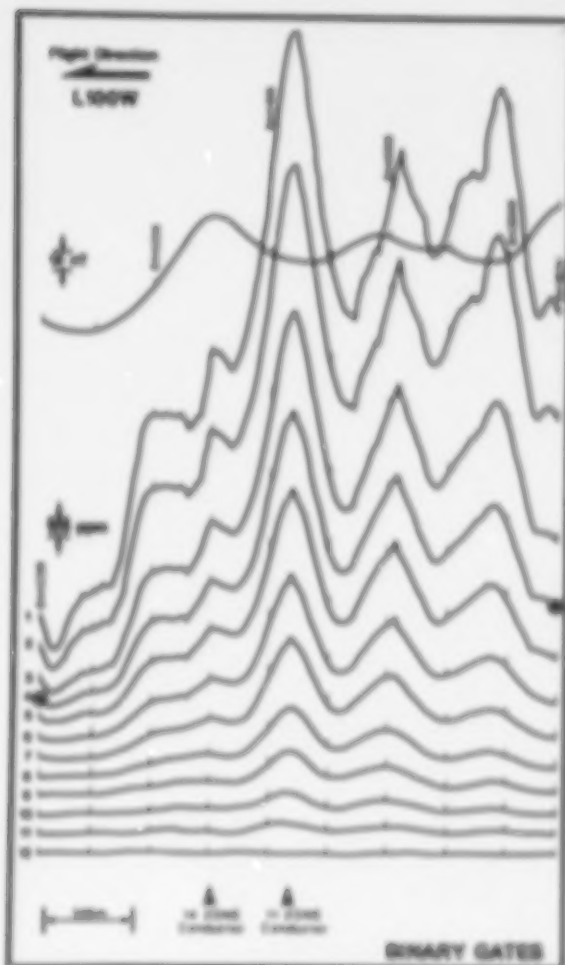


Figure 42.9. Down Lake GEOTEM Profiles: GEOTEM profiles over the 11 and 14 Zone conductors. The receiver pairs were programmed in a pseudo-binary progression. Note that GEOTEM channel 4 is approximately the same as INPUT channel 1. Resolution of the 11 and 14 Zone conductors is improved with GEOTEM.

has a strike length of more than 2000 m, and a maximum width of 100 m.

The Cigar Lake orebody is also a blind deposit, with no radioactive boulder train. The geophysical methods used in the discovery were INPUT and magnetics, followed up on the ground by Crone Fixed-loop FEM (DEEPFEM) time domain EM surveys, to locate the graphitic conductors and provide targets for diamond drilling.

The regional geophysical setting of the Cigar Lake Deposit is shown in Plate 42.4 (see Colour Folio near back of book). The orebody is located within a broad low magnetic area, caused by basement metasediments, situated between two magnetic

high thought to represent Archean granite gneiss. The original INPUT anomalies are weak responses, which ironically may have been caused by conductive lake bottom sediments. Ground EM has been employed in a more regional sense in this area, because the depth to the unconformity is beyond the effective depth of penetration of airborne systems. Conductor zones defined with DEEPFEM show a multiple conductor system curving down from the northeast, which is apparently truncated by an east-west fault zone thought to host the mineralization.

The first regional geophysical technique used in the Cigar Lake area was INPUT. Several 1-2 channel responses were picked from the original survey profiles (see Plate 42.4). The weak amplitudes, and the correlation to lakes suggest that these responses are caused by surficial material. Filtering of the INPUT responses to remove high frequency components, and presentation of the results as a contour map has improved the interpretation (Plate 42.5 (see Colour Folio near back of book)). The INPUT response from a deep conductive source is a long wavelength feature (>1000 m) which is difficult to see in the profiles, and is better suited to contour presentation. Note that because the INPUT system has an asymmetrical transmitter-receiver configuration, responses from different flight directions are contoured separately. Contours of INPUT channel 1 responses indicate the Cigar Lake orebody is located on the south flank of a broad conductive zone.

The Geotrex GEOTEM system was flown over the deposit in 1987 (Thomson 1987). Because the digital GEOTEM receiver does not have an inherent time constant as does the analogue INPUT system, the lateral resolution of conductors is improved. GEOTEM profiles in Figure 42.10 show the amplitude of the channel 3 response as profiles, and the calculated time constants as shaded tones. Within the broad conductive zone north of the deposit, individual conductors can be defined by trends with longer time constants. Note that the time constant of the conductor is independent of the response amplitude.

Ground EM over the deposit was used to follow up the INPUT responses, which led to the discovery of the orebody (Fouquet *et al.* 1986). The Crone DEEPFEM method, which was the first time-domain EM system used here in 1981, employs an impulse waveform transmitted through a large fixed loop, and measures the earth response in eight time windows after current shut-off (Crone 1979). The DEEPFEM profiles in this area typically display multiple horizontal component peaks and migration of vertical component crossovers, which are indicative of a multiple conductor environment. The Cigar Lake conductor (Figure 42.11) gives a strong response which persists through all eight DEEPFEM channels.

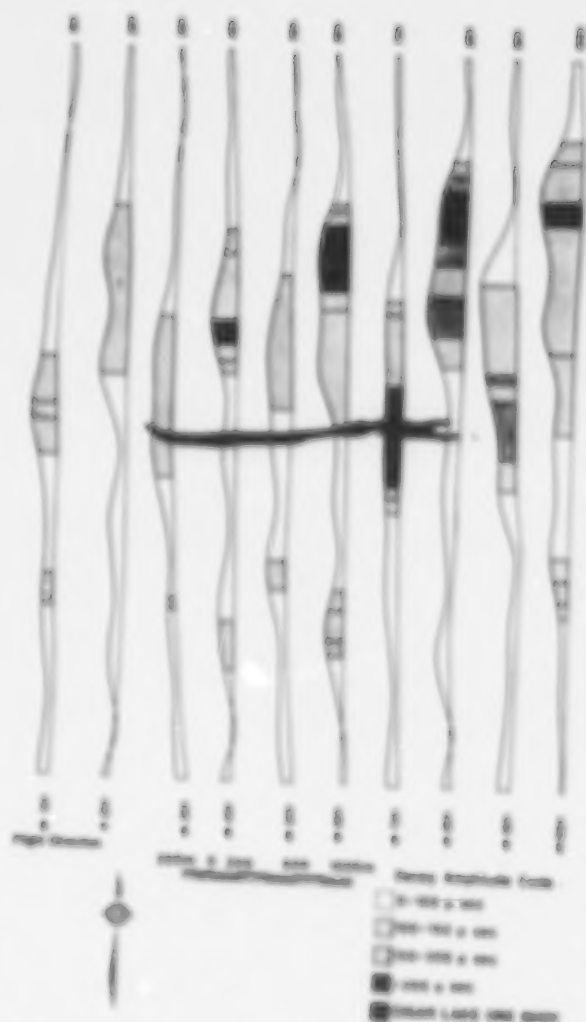


Figure 43.16. Cigar Lake GEUTEM Profiles: GEUTEM profiles over the Cigar Lake Deposit, showing calculated conductance and constant superimposed on channel 1 amplitude.

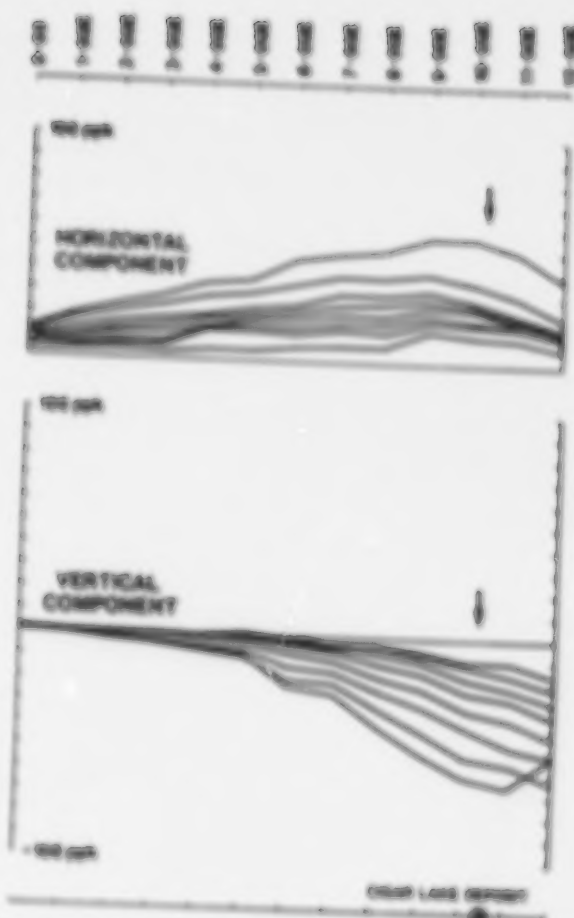


Figure 43.17. Cigar Lake DEEPFEM Profiles: Cross DEEPFEM profiles from Line 4000 over the Cigar Lake Deposit. The Cigar Lake conductor is a strong response which persists through all eight DEEPFEM channels.

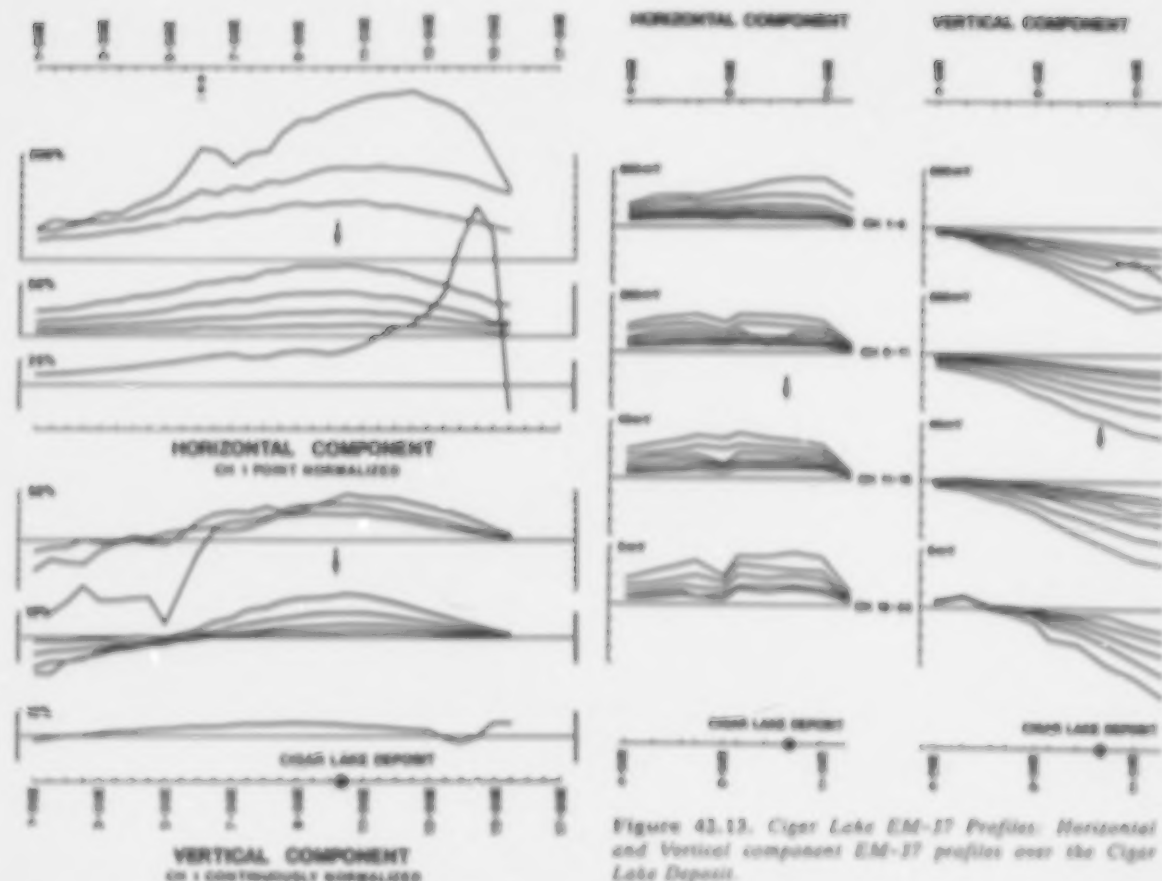


Figure 42.12. Cigar Lake UTEM Profiles: Horizontal and Vertical component UTEM profiles over the Cigar Lake Deposit.

The Lamontagne UTEM® system, which was tested over the deposit in 1986, uses a triangular-shaped waveform transmitted through a large fixed loop, and measures response of the earth in ten time channels. It is not strictly a time-domain system, but has the unique advantage of measuring the step response rather than the impulse response (West *et al.* 1984). The Cigar Lake conductor is again shown as a strong response (Figure 42.12). Until recently, only the vertical component was routinely measured with the UTEM system. However, for deep exploration in the Athabasca Basin it has been found that the best indication of the conductor axis is given by the peak in the horizontal component profile.

The GEONICS EM-37 is a time-domain system similar to the Crone DEEPEM. Test work over the deposit in 1982 also defines the Cigar Lake conductor as a strong, slow decay response (Figure 42.13).

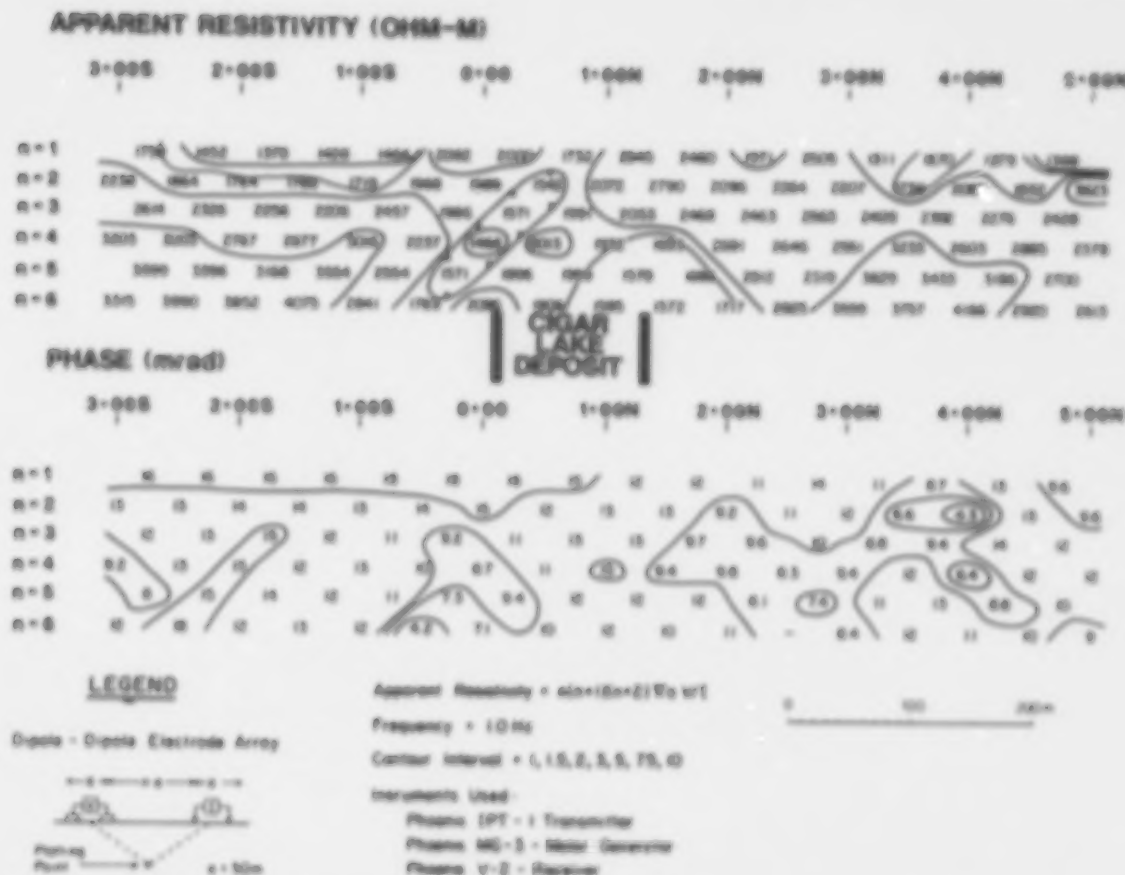
*Registered trademark of Barringer Research Limited.

Figure 42.13. Cigar Lake EM-37 Profiles: Horizontal and Vertical component EM-37 profiles over the Cigar Lake Deposit.

The profiles indicate multiple conductors, interpreted to represent graphitic horizons within the basement rocks.

There is no clear evidence in the results of any of the time domain EM systems of the alteration envelope which surrounds the orebody, or of the clay-rich paleogolite at the top of the basement. The EM responses appear to be solely due to basement graphitic zones. Results from the three time domain EM systems indicate that they are comparable to a depth of at least 500 m.

Several resistivity techniques have been used to map the alteration in sandstone above the orebody. Galvanic resistivity and phase IP results (Figure 42.14) indicate a symmetrical low apparent resistivity zone of less than 1500 ohm-m directly over the Main Pod. This low resistivity zone indicates that the hydrothermal alteration associated with the mineralization extends up through more than 400 m of Athabasca Group rocks. There is no phase IP anomaly associated with the low resistivity zone, indicating a lack of polarizable minerals. The alteration at the top of the bedrock is probably only manifested as an increase in the porosity of the sandstone, which cre-



ates a low resistivity anomaly. There is no macroscopic evidence of the alteration, but an associated geochemical anomaly has been noted (Clark 1987).

Background apparent resistivities of the sandstone are in the range 5000 to 10 000 ohm-m over pelitic basement rocks, increasing to more than 10 000 ohm-m over interpreted granitic basement. The apparent resistivity of the sandstone therefore reflects the underlying basement lithology. Lower resistivity sandstones over graphitic metasediments may have some effect on EM surveys. Current gathering in the sandstone could enhance the secondary field in basement conductors, and account for interpreted EM responses from very deep basement conductors, some of which are beyond the effective depth of penetration of airborne and ground EM systems.

Magnetotellurics is an inductive resistivity method more suited to deep exploration. Controlled Source Audio Magnetotellurics (CSAMT) by Zonge Engineering (Figure 42.15) indicates the Cigar Lake

Deposit is located within low resistivity (<250 ohm-m) metasedimentary basement rocks (Fouquet *et al.* 1986). The high resistivity zone to the northwest of the deposit is interpreted to be caused by granitic gneiss. The Geonics EM-16R profile plotted above the section, which may be equated to the high frequency CSAMT data, shows a similar pattern.

A natural source Audio Magnetotelluric (AMT) survey using the University of Saskatchewan GEOCOM-MT system was carried out on the same profile (Figure 42.16). Cagniard resistivities have been calculated from orthogonal magnetic and electric field measurements, and corrections have been made for topography and near-surface resistivity variations. There is a good correspondence between the CSAMT pseudo section and the Rho YX section, where the electric field is parallel to the survey line. The AMT results outline a low resistivity cone at depth, indicating a wide block of metasediments, with the deposit located at the south edge.

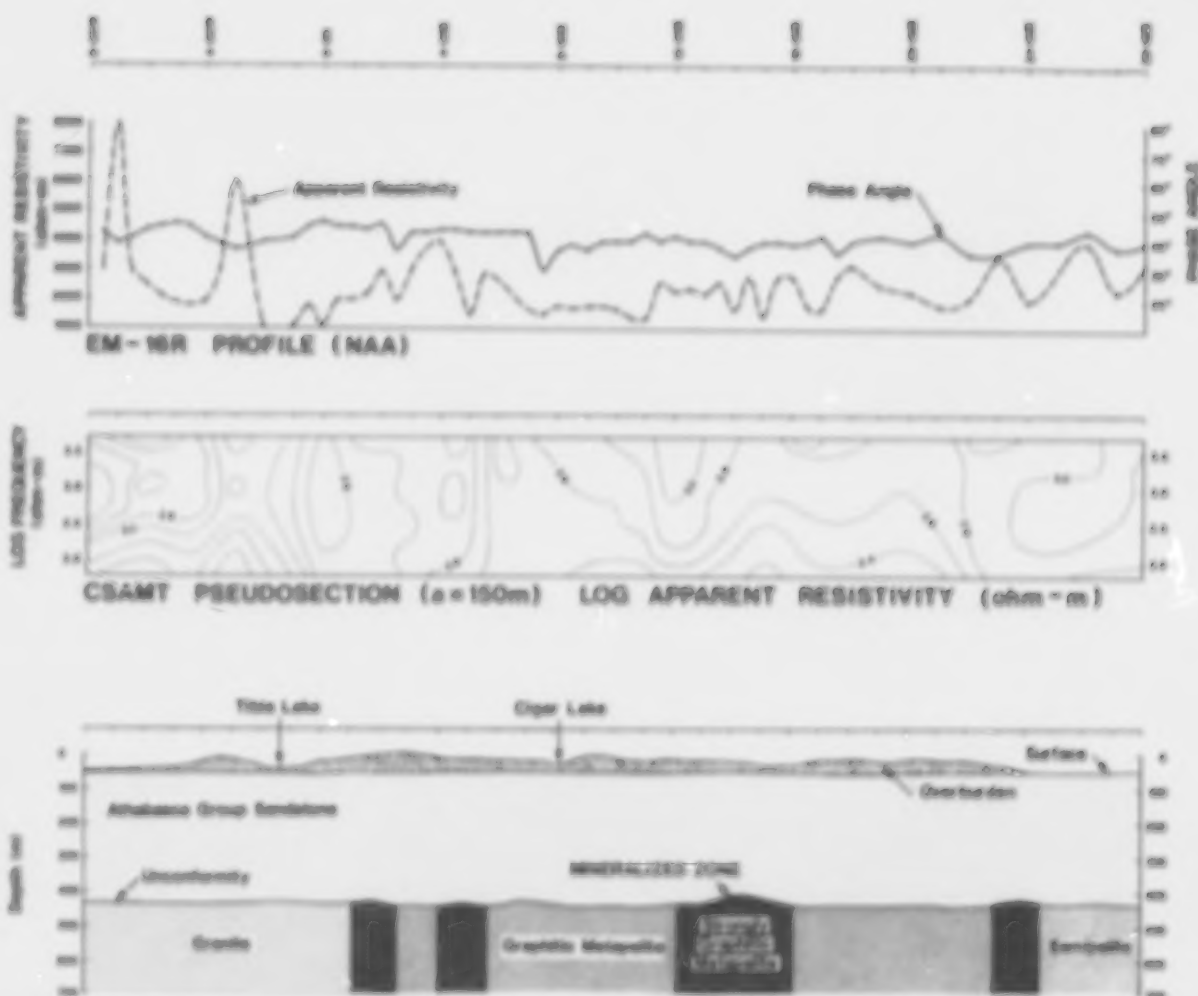
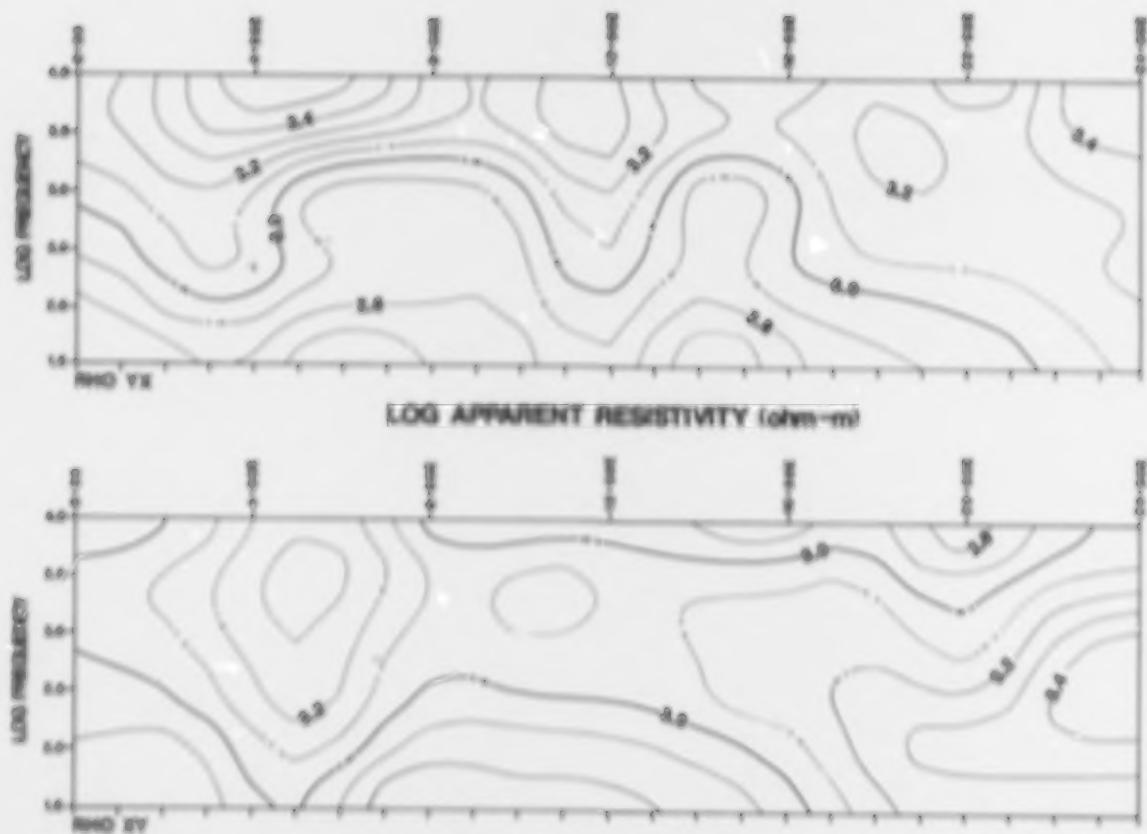


Figure 42.15. Cigar Lake CLAMT Pseudo Sections: CLAMT, EM-16R, and interpreted section from line 0+00 over the Cigar Lake Deposit (after Fougere et al., 1986). A broad low apparent resistivity zone correlates to basement pelitic metasediments.



CREE EXTENSION PROJECT

The regional geophysical setting of the Cree Extension project is shown in Plate 42.6 (see Colour Folio near back of book). The exploration targets are EM conductors within magnetic lows, interpreted to represent graphite horizons in metasediments.

The Cree Extension Project is an earlier stage uranium exploration project located approximately 45 km northeast of Key Lake. The depth to the sub-Athabasca unconformity in this area is in the range 550 to 640 m. Ground EM surveys on this project were used on a reconnaissance scale, as airborne EM systems have not proven effective in this depth range. The Lamontagne UTEM system was employed to outline several long strike length conductors on the flanks of a high magnetic unit interpreted to represent granitic basement. The UTEM profiles from the eastern conductor (Figure 42.17) show a strong response, with horizontal component

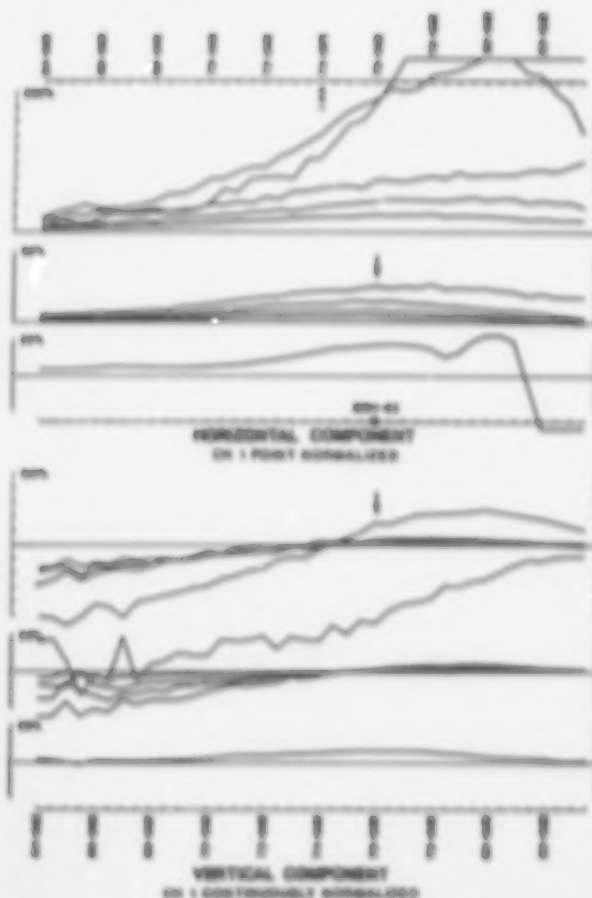


Figure 42.17. Cree Extension UTEM Profiles Line 124500N: UTEM profiles over the eastern conductor from transmitter loops on opposite sides of a multiple conductor zone.

peaks which stack in late time channels, defining one distinct conductive horizon.

Diamond-drill hole number 2 spotted on the eastern conductor was logged with the Crone Borehole PEM system. The Borehole profiles (Figure 42.18) show a strong in-hole response at 570 m. The sub-Athabasca unconformity was intersected at 561 m, and the drillhole continued in semi-pelitic metasediments and passed through a graphitic shear zone at 573 m. The interpretation shown superimposed on a primary field diagram (Macnae 1980) in Figure 42.18 confirms the conductor has been intersected in the drillhole.

A UTEM profile over the western conductor is shown in Figure 42.19. This response looks similar to that over the eastern conductor, although there is some asymmetry and migration of the horizontal component peak for late time channels, which suggests that more than one conductor is present. Diamond-drill hole number 3 was spotted where the horizontal component peaks appear to converge.

The Crone Borehole PEM profiles from hole number 3 (Figure 42.20) indicate a weak off-hole response. The drillhole intersected the sub-Athabasca unconformity at 552 m, and continued through weakly graphitic semipelitic metasedimentary basement rocks. The Borehole PEM interpretation in Figure 42.20, superimposed on a primary field diagram, indicates the drillhole missed the main conductor, which is located approximately 100 m to the east, dipping 60° east.

Diamond-drill holes located on the basis of surface EM profiles cannot be assured of intersecting the main conductor in a multiple-conductor environment and Borehole PEM is often necessary to guide further drilling. Note that even though drillhole number 3 intersected some graphite, the Borehole PEM response indicates a better conductor located off-hole.

Audio Magnetotellurics (AMT) is a resistivity technique for mapping basement geology, which can be applied to this depth range of more than 500 m to the sub-Athabasca unconformity. The AMT sections (Figure 42.21) have been corrected for topography and near-surface conductivity variations. The Rho parallel section (where the electric field is parallel to the survey line) indicates a uniform layered earth with a broad conductive zone at depth. The Rho perpendicular section, which is more sensitive to lateral resistivity changes, also indicates a uniform earth section which is disrupted by two low resistivity zones. The conductors defined by the ground EM surveys are located on the flanks of these two low resistivity zones, which probably represent pelitic metasediments.

Conventional EM surveys can also be used in a resistivity sounding mode. Depth Image Processing (DIP) developed by Lamontagne Geophysics for the UTEM system (Macnae and Lamontagne 1987), stacks vertical component readings from three adja-

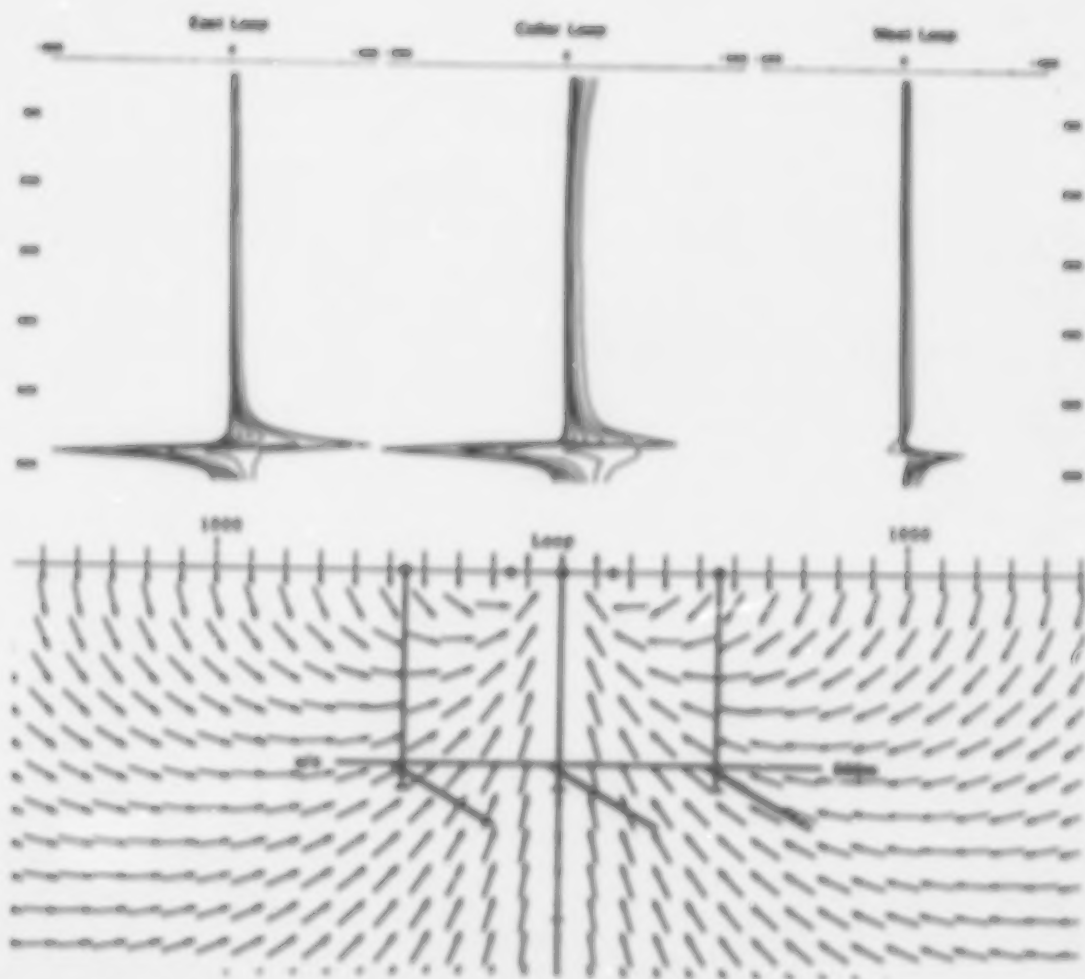


Figure 62.16. Cross Extension Basehole FEM DDH 62: Basehole FEM profiles from transmitter loops in the east, centre, and west of DDH 62. The interpretation shown on a primary field diagram indicates a strong in-hole response.

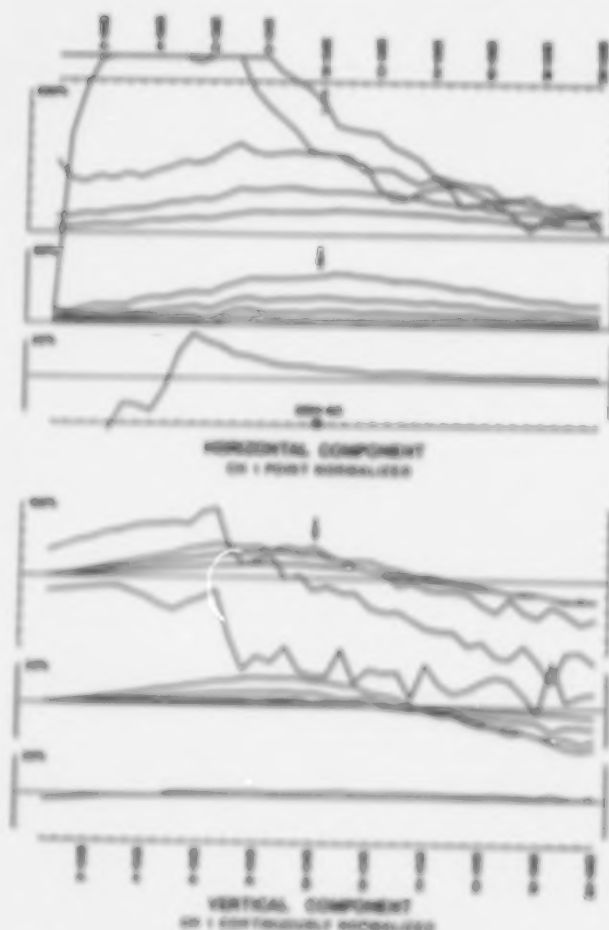


Figure 42.19. Cree Extension UTEM Profiles Line 11+00N: UTEM profiles over the western conductor on Line 11+00N.

cent transmitter loop locations, much like a CDP (Common Depth Point) stack in seismic processing. The three-fold stack is inverted to give a resistivity versus depth section (Plate 42.7 (see Colour Folio near back of book)). This section was completed on the same profile as the AMT pseudo section shown in Figure 42.21. The DIP technique is relatively insensitive to lateral changes in resistivity, but has good resolution of horizontal layers. The sub-Athabasca unconformity is apparent as a sharp change in the resistivity section at approximately 600 m depth. A deep intrabasement conductive block noted in the AMT section is clearly indicated, in contrast to more resistive granitic gneiss to the west.

DISCUSSION

The case histories from the four project areas illustrate the geophysical responses that are associated

with typical unconformity-related uranium mineralization. Although no economic mineralization has been found associated with the Cree Extension conductors, examples from this area illustrate the difficulty in exploring for this type of target at more than 100 m depth.

The physical characteristics of the typical unconformity-related uranium deposit are presented in Figure 42.2. Many measurements of the physical properties of rocks have been made on drill core samples from the eastern Athabasca Basin, from which the ranges of values shown have been derived. There is, however, an inherent sampling bias in drill core measurements. Drillholes are usually located to test EM conductors within magnetic lows. These lows are interpreted to represent metapeliteic basement rocks, which are more favourable hosts for uranium mineralization. Other basement rock types are poorly represented. The physical properties should only be used as a relative guide for the interpretation of geophysical surveys.

The two essential geologic components of the typical unconformity deposit are: graphitic metasediments, and a fault/alteration zone in the overlying sandstone. These components are manifested in geophysical surveys as an EM conductor within low magnetic, high density basement rocks, surrounded by a low resistivity alteration zone. The paleoregolith does not appear to contribute significantly to the geophysical response.

EXPLORATION APPROACH

The examples of geophysical techniques presented illustrate the optimum exploration approach which might be used to locate unconformity-type uranium mineralization in the Athabasca Basin (Figure 42.22). Regardless of the depth, both gravity and magnetic surveys are important methods for mapping basement geology. In areas where the depth to the sub-Athabasca unconformity is less than 100 m, airborne EM is effective in locating basement conductors. In the deeper areas (>100 m) large fixed loop time domain EM methods replace the airborne surveys.

For detailed surveys, the best approach is the use of EM and resistivity techniques suitable to the depth range (see Figure 42.22). In shallow areas (<150 m) the frequency domain methods such as horizontal loop EM and VLF-EM are effective, whereas in deeper areas large fixed loop, time domain EM methods are required. As the depth increases, the resolution of conductors is decreased, and borehole EM techniques may be required to help guide drilling. Conventional galvanic resistivity may also be useful in outlining alteration zones in the sandstone, whereas Magnetotellurics and EM sounding methods can be used to map basement lithologies in the deeper areas.

As exploration in the basin moves into depths to the sub-Athabasca unconformity in excess of

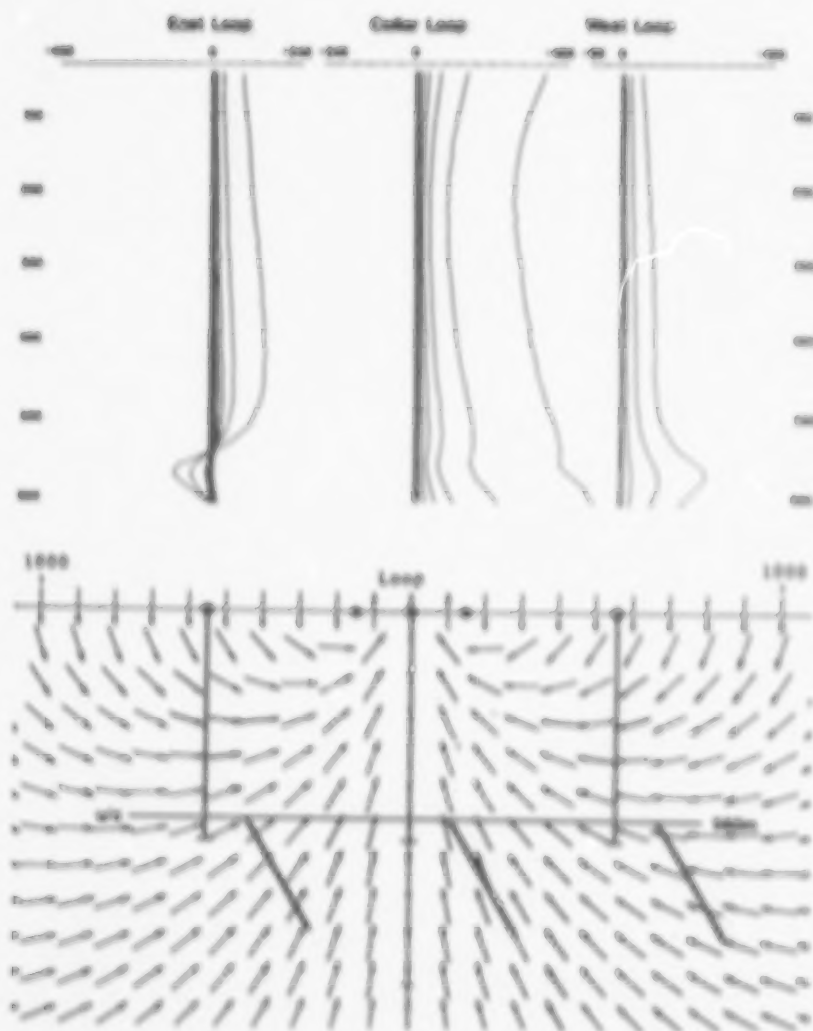


Figure 62.20. Cree Extension Borehole PEM DDH 81: Borehole PEM profiles from transmitter loops east, centre, and west of DDH 81. The interpretation shown on a primary field diagram indicates a weak off-hole response.

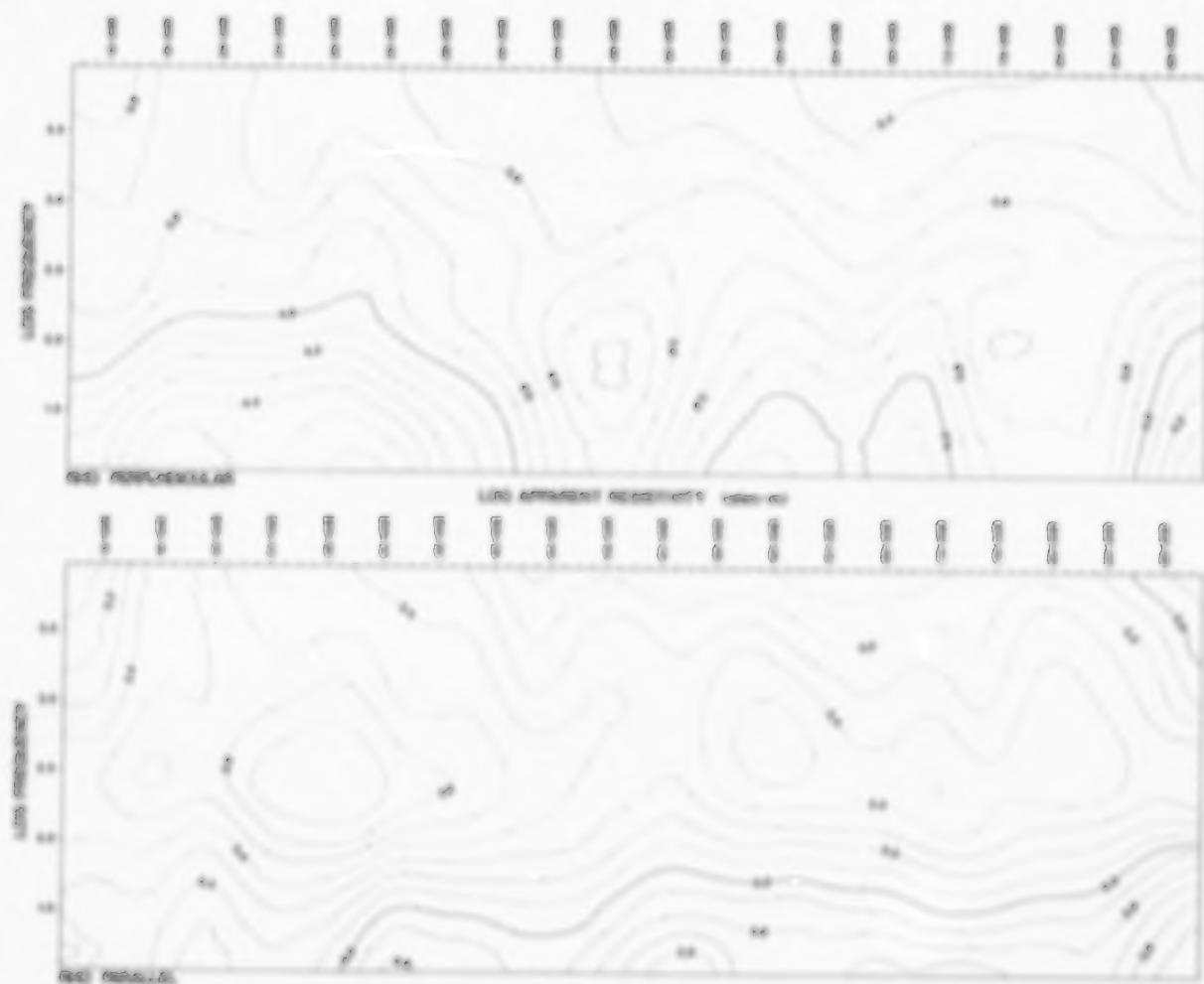


Figure 4L.21. Cross Extension AMT Pseudo Sections: AMT apparent resistivity pseudo sections from $RhoEY$ and $RhoEZ$ polarizations. The discrete EM conductors are located on the flanks of low resistivity basement areas, which represent pelitic metasediments.

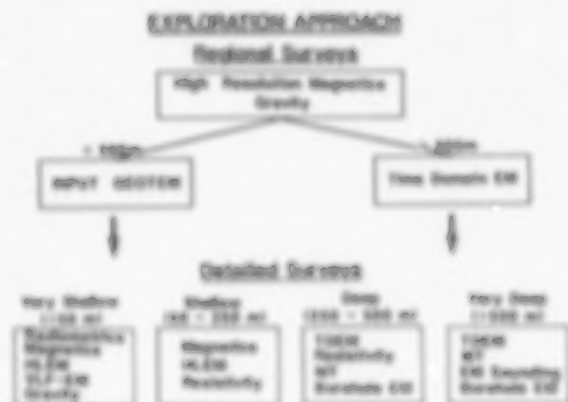


Figure 43.22. Geophysical exploration approach for unconformity-related Athabasca uranium deposits.

700 m, the EM techniques available today are ineffective for defining basement conductors. Other methods which may have some potential at this depth are high resolution seismic reflection, large loop moving source time domain EM, as well as magnetotellurics.

Although variations in the local geology will dictate the actual methods used, this approach should be successful in the search for unconformity-related mineralization in the Athabasca Basin of Saskatchewan. The key to success in any exploration program is an integrated approach using geological, geochemical, and geophysical methods.

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Geochemical Methods: Advances in the State of the Art



43. Design and Planning of Geochemical Programs

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ABSTRACT

Today geochemistry is an essential component in the majority of exploration programs and constitutes between 10 and 15 percent of project budgets. Optimum use of this investment must be made.

Opportunities for improvement of geochemical programs exist in each survey component: design and planning, field sampling, sample processing, chemical analysis, and data presentation and interpretation. This report focuses on opportunities within the design and planning component.

Design and planning concepts and the problem-solving process are reviewed and applied to the execution of geochemical surveys. Four major approaches for improving the effectiveness and efficiency of geochemical surveys are discussed: orientation surveys, modeling and models, integration of geochemistry with other exploration disciplines, and enhancing awareness and appreciation of geochemical techniques amongst explorationists. Future trends and opportunities are suggested.

INTRODUCTION

Exploration geochemistry is used to find evidence that will aid in the discovery of mineral deposits. Over the last 15 years, emphasis in the mining industry has changed from base metals, to uranium, to precious metals. These shifts have required considerable modification of exploration techniques to meet the detection requirements of each new commodity. Concurrently, advances in the geological and allied sciences, and technological progress, have greatly expanded the number of alternative approaches to exploration, including many based on geochemistry. Today, geochemistry is an essential component in most programs in mineral exploration and development. Recent estimates suggest that between 10 and 15 percent of exploration budgets are allocated to geochemistry (Claeys 1984). The challenge in today's competitive exploration environment is to ensure optimum use of this investment.

Geochemical programs consist of five major components: a) design and planning; b) field sampling; c) sample processing; d) chemical analysis; and e) data presentation and interpretation. Opportunities for improvement exist in each. Those afforded by the design and planning stage are consid-

ered here. This paper is concerned with: a) general concepts of design and planning; b) the application of design and planning to the execution of geochemical surveys; and c) selected approaches to improve the effectiveness and efficiency of geochemical surveys. Future trends and opportunities are suggested.

While this presentation focuses on design and planning of geochemical programs, it is axiomatic that geochemistry is only one approach within integrated mineral exploration. Cooke and Davidson (1978) discussed the broader issue of integrated programs, and Hodgson *et al.* (1982) provided examples for gold exploration in Canada. However, the concepts and approaches discussed here for geochemical programs are equally applicable to planning and design of other program components, or the total integrated exploration project.

DESIGN AND PLANNING

GENERAL CONCEPTS

Both design and planning are incorporated in the problem-solving process discussed here, where the terminology and philosophy are taken largely from Dieter (1983). Design satisfies a need by the pulling together of something new, or by the new arrangement of existing things. Planning identifies the key activities in a project and orders them in the sequence in which they should be performed. Scheduling, which will not be addressed in this paper, is often considered to be a component of planning. It consists of putting the plan into a specific timeframe.

Design demands both science and art. The science comprises techniques and procedures that can be learned; mastery of the art is gained through extensive practical involvement. Good design requires both analysis and synthesis. Analysis entails simplification through separating the actual situation into manageable parts. Synthesis is concerned with reassembling these component parts into a workable whole.

The problem-solving process consists mainly of: a) recognition of needs; b) definition of the problem; c) information gathering and definition of alternatives; d) evaluation; e) selection of solution strategies; f) implementation; and g) review and revision. These steps are listed in apparent chronological or-

der; however, the problem-solving process is iterative (Kaufman 1982; Dieter 1983).

The utility of the problem-solving process is greatly affected by the distinction between means and ends. Appreciation of this distinction in mineral exploration can significantly improve effectiveness and efficiency of the project. Ends are the results sought. Means are the tools, techniques, or processes employed to achieve desired ends. This distinction in mineral exploration has been clearly expressed by Muessig (1979):

"To be sure, exploration uses science, but it is not science, since its aims are fundamentally different. Science strives for understanding, exploration strives for discovery — with or without understanding — by whatever means."

In the timeframe of an exploration project, the utility of any alternative approach (means) must be evaluated solely on the basis of its contribution to discovery (ends), not on its innate scientific good.

A problem is defined in terms of moving from the present state to the desired state, and a need is the difference between the current situation and the desired results or ends. The problem must be defined by a statement of the current situation, a statement of the desired results, and a precise, measurable description of the discrepancy between the two. Problem definition serves to initiate activity. It is also the means of focus and control during the problem-solving exercise, the means of determining if the problem has been solved, and the means of identifying what revision or corrective action is required. Once this is recognized, the importance of a precise, complete problem definition is more fully appreciated.

PROBLEM-SOLVING IN EXPLORATION GEOCHEMISTRY

The solution of a problem in exploration geochemistry typically follows the seven step sequence defined above as the problem-solving process. Each of these steps, as well as substeps within major steps, can be analyzed in terms of: a) input or available resources; b) tools, methods or techniques available for evaluation; and c) output or results. Products from these steps are synthesized to solve the initial problem. Available resources, tools, methods, and techniques applicable to the design of an exploration geochemistry project are reviewed in this section. Output or results are illustrated by an example of the problem-solving process applied to geochemical survey design.

Available Resources

Bailly (1972) succinctly described the explorationist's five key resources as: a) geological knowledge; b) exploration technology; c) time; d) money; and e) people. People who are dedicated to discovery and who control the use of the first four resources are the most important of these factors.

The basic principles and applications of exploration geochemistry, constituting the first two key resources, are reviewed in Rose *et al.* (1979), Levinson (1980), Hood (1979), and Garland (1989). Improvements in the technical quality and use of any of these resources constitute the means of strengthening survey design.

Project Constraints

A comprehensive exploration project includes geochemical surveys that are carried out within such recognized constraints as: a) commodity sought; b) acceptable types of geological targets; c) geographic and political restrictions; d) exploration entry point; and e) available resources. These constraints may appear to be either problems or opportunities. They are here considered to be opportunities because they define the information needed to design the geochemical survey.

Definitions of commodities sought and acceptable types of geological deposits provide information on the petrology, mineralogy, dimensions, and shape of the targets. These data affect sample preparation, chemical analysis, potential geochemical associations, and pathfinder elements that could be exploited in survey design. Further, these definitions contribute to design decisions that control the pattern and density of sampling.

Geographic location of the project area defines the differences in approach that are dictated by climate, physiography, weathering, soil types, dispersion characteristics, and the availability and spacing of different potential sample media. Access and the availability of service facilities are also determined by geographic location.

The exploration entry point defines the survey scale which further restricts sample media and sample spacing. The history of prior exploration in the area bears on the conceptual basis and technological level adopted in the proposed project.

Available resources, geological knowledge, exploration technology, time, money, and personnel may greatly restrict options for the geochemical survey. Thus, overall project constraints largely determine the design of geochemical surveys.

Improving Survey Design

Improving survey design is discussed here in terms of general strategies and specific approaches.

General Strategies Two general strategies must be considered. The first is to employ conventional or traditional techniques in the geochemical survey. The second, or "new panacea" strategy, is to use some recent breakthrough in geological concepts and/or exploration technology.

The first approach might be appropriate where the area has not previously been surveyed, or where an earlier survey is believed to have been improperly

executed. Extreme care should be exercised in the latter conclusion if resources are not to be wasted through duplication.

The second approach offers considerable potential for competitive advantage if the "new panacea" method achieves only 25 percent of its initial potential. The danger in this strategy is the pressure to employ these techniques before they are fully tested and understood. In fact, the capabilities and limitations of a new technique commonly take years to adequately assess. A balanced approach based on a realistic understanding of the options available in a specific situation is recommended.

Specific Approaches Geochemical survey design can be improved by specific approaches based on the types of sample media that convey a geochemical dispersion signal from mineralization, and knowledge of the mode of occurrence of the metals within these materials. Field sampling methods focus on the necessary medium, and on the appropriate procedures for sample collection. Physical and chemical separation techniques isolate the fraction or phase of the sample that contains the mineralization signal. Sieving, panning, and heavy liquid separation are examples of the former procedures, and partial or selective chemical extraction techniques are examples of the latter. Geochemical associations that characterize favourable host rock, alteration, or mineralization can be exploited directly through multi-element analysis followed by statistical treatment of the geochemical data. Commonly, several specific approaches are used in combination to further optimize the effectiveness and efficiency of the survey.

Evaluation Criteria

Criteria to evaluate and rate alternative techniques must be established to optimize survey procedures. Under ideal circumstances, an exploration survey might measure a single parameter capable of indicating the presence or absence of mineralization and, where positive, indicate the direction for follow-up

action. Achieving these ends implies that the technique (means) is specific for the target sought, is direct, and is readily interpreted. Further, this ideal technique should be appropriate for use over a wide range of survey scales, be easily performed by unskilled personnel, and be inexpensive. No such procedure exists. Hence, evaluation criteria are needed to assess available but less than ideal techniques.

Specificity for the target can be addressed through a knowledge of the mode of occurrence of the geochemical signal in the utilized sample media. This signal can be enhanced through an appropriate combination of techniques applied to the sample medium, the sample fraction, and the chemical analysis. This required information is commonly obtained from orientation surveys.

Directness of survey procedures tends to carry the implication that the commodity sought is its own best indicator. However, results of analyses for different members of the geochemical suite or pathfinder elements generally provide more reliable indicators over a broad range of survey scales, given the variation in metal mobility with scale (Warren and Delavault 1956). James (1957) described an early example of the use of arsenic in soils as an indicator of gold mineralization (Table 43.1).

Results of a survey would be readily interpreted if a large difference existed between the response from mineralization and the response from barren terrain. Contrast, which is the ratio of the anomalous response to the average background value, or to the threshold (the upper limit of the background range), provides a measure of the difference in response and is useful for assessing the relative interpretability of alternative methods available for the survey. Contrast frequently varies with stage of exploration (Figure 43.1).

Dispersion distance is the distance over which a combination of specific elements, in a particular fraction of a given type of sample, is recognizably anomalous. Dispersion distance provides a measure of the utility of that combination at various sampling

TABLE 43.1. EXAMPLE OF ARSENIC AS A PATHFINDER FOR GOLD MINERALIZATION (after James 1987).

STATION	As CONTENT (ppm)	CONTRAST*	Au CONTENT	CONTRAST**
			(ppm)	
300 N.	40	4	0.1	1
50 N.	100	10	0.1	1
10 N.	480	48	1.0	10
0	1000	100	3.0	30
15 S.	560	56	1.0	10
50 S.	190	19	0.5	5
300 S.	80	8	1.0	10
400 S.	10	1	0.25	2.5

Assumptions: *As Threshold = 10 ppm;
**Au Threshold = 0.1 ppm.

Sample Type: Soils

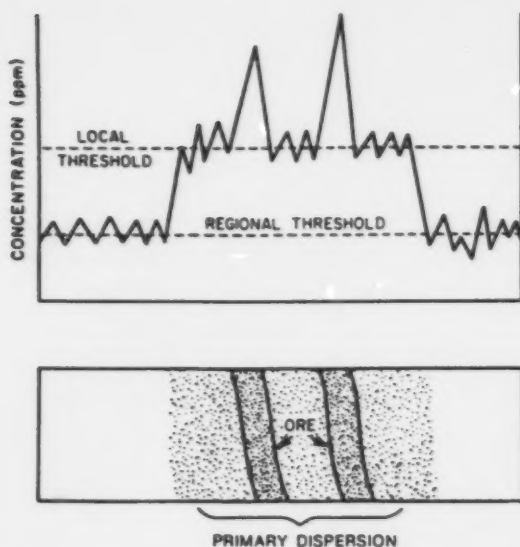


Figure 43.1. Illustration of regional and local threshold (from Levinson 1980).

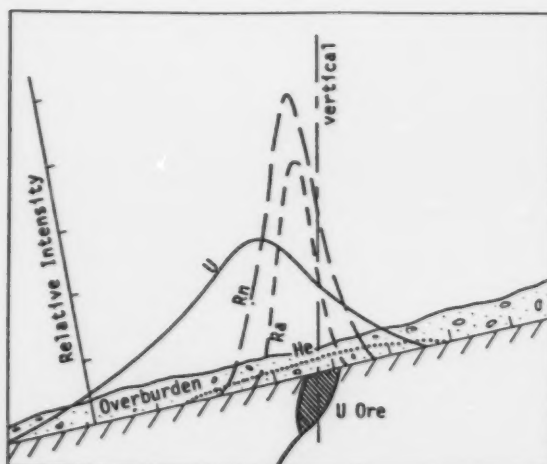


Figure 43.2. Illustration of variable dispersion characteristics of members of the geochemical association related to uranium mineralization (from Dyck 1975).

densities and diverse surveying scales. Dyck (1975) provided an excellent illustration from exploration for uranium (Figure 43.2).

Owing to natural and/or to induced variability, absolute metal concentrations are not generally valid for the definition of an anomaly. Relative differences are more commonly used in evaluating the data from a geochemical survey. Locally, instead of the intensity and extent of the anomaly, the shape or form of the dispersion pattern best indicates a mi-

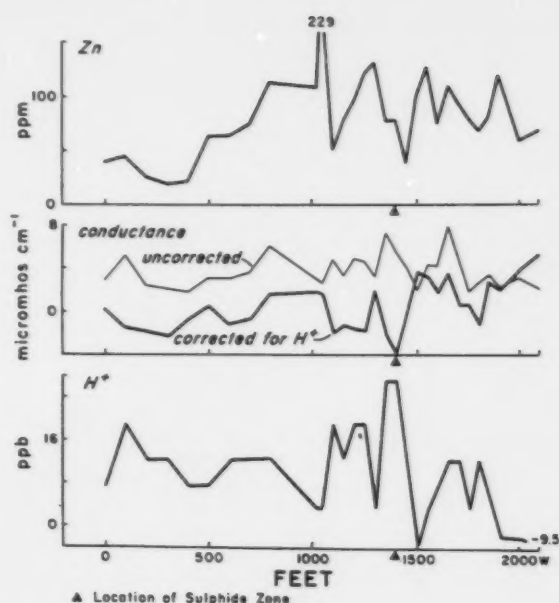


Figure 43.3. "Rabbit-Ear" electrogeochemical anomaly as an illustration of anomaly definition by dispersion pattern shape and form (after Govett 1986).

neralized environment, as shown by the "rabbit-ear" pattern produced by some electrogeochemical and gas geochemical techniques (Figure 43.3).

The technical criteria defining the geochemical survey must be further evaluated through nontechnical considerations such as cost, time, and availability of resources, which frequently control the choice of method. This strategy must not unduly compromise the capability for discovery of the selected approach.

Example

A preliminary broad-scale geochemical soil survey was conducted for visible free gold associated with swarms of tourmalinized quartz veins in a thick sequence of mafic volcanic rocks in an area of temperate climate, where bedrock is almost completely covered by deep residual overburden. Only one small outcrop exposes the mineralization, and geophysical techniques were not effective in delineating the mineralized zone. The geochemical survey employed a weak acid extraction of metals in the minus 80-mesh fraction of samples from the B horizon of podzolic soil. Because of potential problems in sample representativity associated with the coarse-grained gold, reliance was placed on boron as a pathfinder element. Initial results revealed a very low-contrast anomaly for boron (less than 2X threshold) associated with the exposure, as well as several other possible anomalies. Grades for gold and widths of mineralization at the exposure would make the deposit economic if the mineralized zone could be extended. Support for further evaluation of

the property would be difficult to generate until a more definitive and reliable procedure for exploration could be developed. What can be done?

The problem in this example is to improve the procedures used for the geochemical survey to raise confidence in the evaluation of this promising property. Anomalies showing 5X contrast are wanted by the backers before funds will be advanced to do further work. However, funds are available to conduct an orientation survey to refine the exploration design to meet these requirements. At this point, a precise statement of the problem can be made: the present survey design can only provide up to 2X anomaly contrast; 5X anomaly contrast is required to proceed confidently with evaluation of this property; therefore, the technical problem is to find a means to obtain this specific improvement in contrast. The improvement must not result in more than a ten percent increase in overall survey costs, and it must be available in two weeks or the resources will be allocated to another project. These nontechnical criteria must be added to the problem definition.

The orientation survey is initiated with the testing of a variety of combinations among particle size, metal extraction, and trace element suites determined. Results are evaluated with respect to the contrast specification of the problem statement. Two possible solutions emerge. One shows that if the plus 30 minus 80-mesh fraction is analyzed only for total boron, the results provide a 5X contrast while keeping increases in the cost of the survey below the ten percent requirement. The other solution shows that if the minus 250-mesh fraction is analyzed by partial extraction for a suite of elements including boron, the results provide a 10X contrast. However, use of the second solution would raise the cost of the survey by 20 percent. Which solution should be chosen?

Solutions must be identified that meet the minimum technical requirements, otherwise, the entire problem should be reassessed. Next, solutions that meet nontechnical requirements must be identified. This example requires that the first solution be selected: analyze the coarse fraction only for boron. The problem definition was used to define precisely the problem, to control the selection of alternatives to be assessed, and to select the solution that satisfies the problem definition. Thereafter, when this change is implemented in the survey design, the outcome must be evaluated against the need for more definitive and reliable identification of geochemical anomalies for selection of follow-up areas, as stated in the problem definition.

The problem-solving process permits appropriate modification of the problem definition based on improved technical insight into the problem or on changes in nontechnical specifications. However, the problem should be re-analyzed using the problem-solving procedure to assure that the proposed

change in survey design will satisfy the minimum requirements of the problem definition, and thereby constitute a valid solution.

SELECTED APPROACHES TO IMPROVE GEOCHEMICAL SURVEY DESIGN

The approaches discussed here are: orientation surveys; modeling and models; integration of geochemistry with other exploration disciplines; and enhancing awareness and appreciation of geochemical techniques amongst explorationists.

ORIENTATION SURVEYS

An orientation survey is used to establish optimum procedures for routine field sampling, sample processing, analysis, and interpretation for the design of a program that will permit confident recognition of true anomalies (Table 43.2). The orientation survey should ideally be conducted before routine survey work is initiated. Alternative survey procedures are assessed in the light of both technical and nontechnical project requirements.

This type of survey is unnecessary where available information fills the needs raised in Table 43.2. Experience suggests, however, that these needs are seldom known, because appropriate techniques vary by type of deposit sought and area of search, and appropriate techniques have not been established for all combinations of target and area. Further justification for the orientation survey is found in the considerable human and technical resources that will be committed to the geochemical survey, and in the desire to maximize specific discovery information from each component of the exploration program. The small commitment in time and money to establish appropriate survey specifications at the start of a project may well prevent wasting the substantially larger survey budget on a poorly designed program.

The information to address needs raised in Table 43.2 may be obtained through four approaches: a) traditional orientation survey; b) case history; c) consultation; and d) combinations of these. Each is addressed below.

TABLE 43.2. REQUIREMENTS FOR AN ORIENTATION SURVEY.

1. Clear understanding of target type
2. Understanding of surficial environment of search area
3. Nature of dispersion from mineralization
4. Sample types available
5. Sample collection procedures
6. Sample size requirements (e.g. Au)
7. Sampling interval, orientation, and density
8. Field observations required
9. Sample preparation procedures
10. Sample fraction for analysis
11. Analytical method required
12. Geochemical suite for analysis
13. Data format for interpretation

Traditional Orientation Survey

Field work, laboratory work, and interpretation of data are involved in the traditional orientation survey. Field areas are selected for the survey that contain the range of geological and surficial environments and types of mineralization anticipated in the area of the proposed project. Various sample media are collected at the scale or scales to be used in the routine surveys. To err in the orientation on the side of oversampling assures adequate data to establish optimum sample spacing at each scale to be used in the program. Samples are processed and chemically analyzed to define technical and nontechnical procedures for each of the other major stages of the program: field sampling, sample processing, chemical analysis, and data interpretation. The data from the orientation survey are evaluated against the project requirements, and the optimum survey specifications determined. Potential questions relevant to each stage of the program are enumerated below.

Field Sampling What sample media are available? Of these, which are both geologically and statistically suitable to reflect dispersion from mineralization? Is the mode of occurrence of the mineralization known? What control is necessary to monitor field sampling representativity? Do seasonal climatic influences affect access and/or chemical response? Are specialized field sampling techniques or equipment required? What does that imply for the training of field personnel? What is the minimum sample density for confident detection of anomalies at each proposed scale? How are the samples to be stored and shipped? What field observations are necessary to complement the analytical data and to support interpretation?

Sample Processing Are options such as screening or mineral separation desirable? Would advantage accrue by processing the samples in the field? Is the geological and statistical integrity of the original sample maintained? If not, does the change maintain or enhance the representativity of the signal from mineralization? What are the advantages and limitations of the equipment used for sample processing? What type of control system is necessary to monitor both equipment and operators?

Chemical Analysis What combination of analytical approach and elemental suite is appropriate to detect and enhance the signal from the sought mineralization? What is the contrast and what quality of analytical data is required? What are the capabilities of the equipment and personnel? Can some or all of the analyses be done in the field? What type of quality control system is appropriate for the analytical methods? Is control integrated with evaluation systems for the representativity of samples at the field sampling and sample processing stages? What requirements for data reporting are employed to facili-

tate subsequent needs in the management and interpretation of data?

Data Interpretation Would computer-based statistical techniques be useful or required to interpret fully the geochemical data? Are facilities available for computation of basic statistics and the plotting of geochemical data? Are these techniques and the necessary personnel available? Are base map scales coordinated with those of topographic and other geoscience data bases to facilitate interpretation?

Discussion These questions are by no means exhaustive, but they indicate issues that require attention and that orientation surveys should address. When technically successful approaches have been identified, alternatives can be screened using such non-technical constraints as cost and logistics.

Case History Approach

The case history approach commonly constitutes the first attempt to define and validate specifications for project design. Under conditions where a traditional orientation survey cannot be conducted, many questions can be answered by referring to the experience of others as recorded in published case histories, unpublished company and assessment reports (Ainsworth 1979), or the conceptual models volumes of the Association of Exploration Geochemists (for example, Bradshaw 1975). The case history approach requires that the sources be critically evaluated before their results are used in a survey design. Less commonly, orientation surveys may be based on application of fundamental geological and geochemical principles (Naldrett *et al.* 1984). Library research can be a most cost-effective exploration technique.

Consultation Approach

A great deal of useful information can be obtained at nominal cost from government agencies; companies furnishing analytical services, equipment, or supplies; and universities. Not to be forgotten are former classmates or colleagues. Private consultants often provide cost-effective, unique or specifically relevant information.

Combination Approach

In reality, a combination of the above approaches is used. The objective of the orientation survey is to acquire the information necessary to design an effective program of geochemical exploration.

Discussion

Technical aspects of the design of orientation surveys have been emphasized on the premise that these requirements must be satisfied before commencing the main geochemical survey. Available resources and project constraints, coupled with experience and common sense, provide means of reducing

the potential number of geochemical approaches to a manageable level for proper technical evaluation. Nontechnical considerations are built in throughout the process; however, greatest attention to this aspect should be reserved until viable technical alternatives have been documented. The design phase provides a systematic and rational basis for assessing alternatives from both technical and nontechnical perspectives.

MODELING AND MODELS

General Methodology

The modeling process and the models themselves provide means to synthesize the ever-enlarging base of information on mineral deposits and exploration regions, and to apply it to a particular exploration problem. Modeling and models have been used successfully in both economic geology in general (Adams 1985), and exploration geochemistry in particular (Bradshaw 1975).

A model has been described by Dieter (1983) as a functional idealization of a real-world situation used to aid in the analysis of a problem. Adams (1985), referring to mineral deposits, defined a model as a combination of data and concepts, presented as text, formulae, graphics, and/or physical simulation. He recognized content and method of presentation as the two dominant aspects of modeling. Expectations from the modeling process and models were regarded by Adams (1985) to include identification of the most informative and reliable characteristic of a deposit, identification of geological characteristics for a range of scales, and definition of both the average and range of variation of each characteristic. Models and modeling were also seen by Adams (1985) to aid in communication and understanding, and to minimize the uncertainty, risk, and cost of exploration. Of equal importance is to understand that a model is not complete: inclusive, final, or a panacea!

Preparation of a model requires: precise definition of the feature to be considered; compilation of available data; synthesis of the data to establish the "mean and variance" of each characteristic; interpretation; and identification of the most diagnostic criteria for the recognition of the target. These steps closely resemble the components of the problem-solving process outlined above. A model should be developed to the extent that it provides the exploration program with a competitive advantage (Figure 43.4).

Models for use in exploration geochemistry are classified as traditional, which refers to surficial geochemical and lithogeochemical models; and methodological, which refers to procedural or operational models.

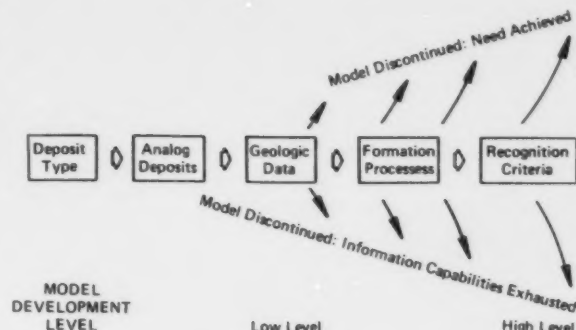


Figure 43.4. Data-process-criteria model preparation steps and model development termination criteria (from Adams 1985).

Traditional Models

The conceptual models volumes of the Association of Exploration Geochemists synthesize, by physiographic domain, extensive data from surficial geochemical exploration including the Canadian Cordillera and the Canadian Shield (Bradshaw 1975); Scandinavia and east Greenland (Kauranne 1976); the Basin and Range Province of the western United States and northern Mexico (Lovering and McCarthy 1978), and Australia (Butt and Smith 1980; Smith 1982). The same approach has been applied to other environments on more modest scales: tropical rain forests (Bradshaw and Thomson 1982); tropical and sub-tropical environments (Butt 1987; this volume); and areas of preglacial deep weathering (Smith 1987). These syntheses arose from a need by geologists and geochemists engaged in mineral exploration for ready access to empirical information on geochemical prospecting, and to the basic principles being developed in the global field of landscape geochemistry (Fortescue and Bradshaw 1973; Fortescue 1980). Each volume contains an overview of the regional bedrock and surficial geology, mineral deposits, physiography, climate, and soils; conceptual or idealized models to synthesize data and summarize geochemical dispersion processes; and abbreviated case histories used to construct the models. The first volume includes an overview of landscape geochemistry and recommendations for standardizing the collection of data for the refinement and development of future models (Bradshaw 1975).

Landscape geochemistry is used as the framework for presenting data from geological and geochemical prospecting. Idealized models in the form of block diagrams illustrate the relationship of anomalous geochemical dispersion patterns within a given landscape configuration. Idealized cross-sections portray geochemical dispersion characteristics in a continuous vertical section, and idealized prisms emphasize vertical changes within a profile (Figure

43.5). These conceptual models have been developed specifically with the explorationist in mind. They constitute the departure point for project design and planning.

Lithogeochemical models are often classed as metal zonation models and incorporated within the structure of models for individual types of mineral deposits. This may be advantageous if improved overall understanding of the type of deposit and greater utilization of data from rock geochemistry are promoted. However, lithogeochemical data tend to lack sufficient analytical quality control and sample representativity can be inadequately appraised. The result may be a less comprehensive and reliable interpretation of the geochemical data resulting in a decrease in the contribution of lithogeochemistry to the exploration project. For these reasons, a separate interpretation of lithogeochemical data is rec-

ommended prior to incorporation into the mineral deposit model.

Lithogeochemical exploration for bulk tonnage gold deposits illustrates the evolutionary character of geochemical models. The initial rock chip geochemical survey carried out at Cortez, Nevada, by Erickson *et al.* (1966) was based on the concept of a leakage halo which was later found to be inappropriate (Erickson, personal communication, 1987). Nevertheless, the results indicated that lithogeochemical exploration utilizing what later was to be termed the Carlin trace element suite, could contribute significantly to exploration for this type of deposit. No specific genetic interpretation was implied. The Carlin trace element suite is an empirical model. Recently, conceptual models for this type of deposit have been developed. They include both the factual chemical data and genetic interpretations of these data based on current theories of hydrothermal processes and tectonics (Bagby and Berger 1985; Silberman and Berger 1985). The progression from empirical to conceptual models proceeds from expanding knowledge over time, recognition of limitations in the initial model, and competitive advantage to be gained by improvement of the model.

Methodological Models

A methodological model refers to a model which specifies a sequence of modeling steps to achieve an objective (Adams 1985). The numerical character of geochemical data permits formal assessment of the reliability of information; hence, the overall reliability of the model can be thoroughly evaluated. Two illustrations of the evaluation of the reliability of information are presented: a) the adequacy of the quality of analytical data to meet a specific requirement; and b) the statistical stability of the data on a geochemical map.

The adequacy of the quality of the analytical data can be evaluated by using prescribed analytical quality control procedures to establish the precision and accuracy of the data (Fletcher 1981). The results of quality control must be interpreted in the context of the problem at hand. As an example, niobium was determined by semi-quantitative emission spectrography in a surficial geochemical orientation survey carried out over a mineralized body of carbonatite. Replicate analytical results indicated that precision was greater than ± 50 percent at the 95 percent confidence level (Closs and Sado 1982). Initial subjective assessment of this precision would suggest that the data were too unreliable for use in geochemical interpretation. However, the replicate data must be evaluated in its geochemical context. Although the abundance of niobium in soils is about 20 parts per million (Levinson 1980), in mineralized phases of the carbonatite, niobium reaches concentrations of hundreds to thousands of parts per million (Figure 43.6). When the concentrations of niobium are compared using the limits of ± 50 percent

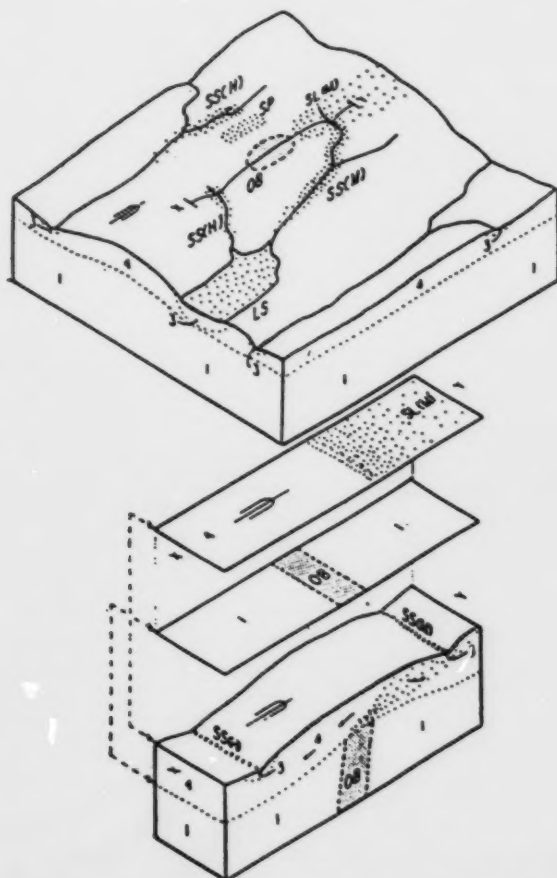


Figure 43.5. Example of Association of Exploration Geochemists Conceptual Models: Model A1 (Shield). Idealized models for geochemical dispersion of mobile elements in areas of thin lodgement till (from Bradshaw 1975).

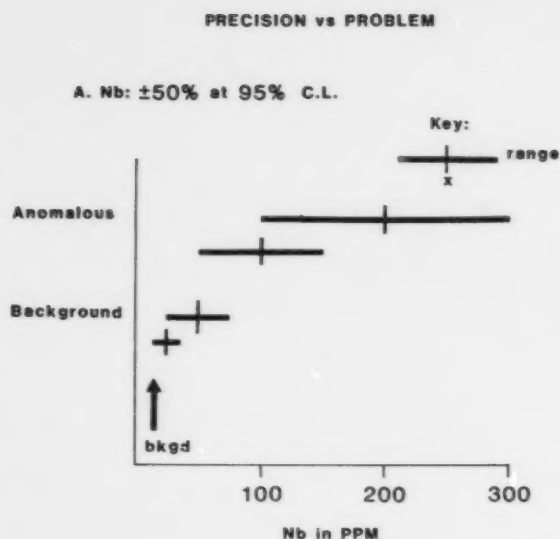


Figure 43.6. Illustration of the need to evaluate analytical precision of data with respect to the specific problem at hand. Niobium data, with ± 50 percent precision at the 95 percent confidence limit, is quite adequate for confident anomaly recognition in overburden associated with a mineralized carbonatite environment, Prairie Lake, Ontario, Canada (after Closs and Sado 1982).

analytical reproducibility limits about each data point (Figure 43.6), the analytical results for niobium are seen to be sufficiently precise to distinguish anomalous from background samples of carbonatite. Analytical quality control can be considered to be a methodological geochemical modeling procedure that permits assessment of the reliability of interpretations based on the analytical data, and of subsequently constructed geochemical and/or geological models.

Geochemical data are commonly presented as patterns on maps for purposes of geological interpretation and communication. All variation within the geochemical pattern is assumed to portray geologically significant differences across the survey area. This assumption implies a highly unlikely lack of significant variability in the data introduced by field sampling, sample processing, or chemical analysis. How can these constraints be formally assessed? Analysis of variance (ANOVA) techniques provide a means of modeling these sources of variability (Miesch 1976).

The necessary input for ANOVA is replicate data for each major source of variation. Results from the statistical analysis provide estimates of the proportion of the total variability of the geochemical data resident in each source considered. From these results a meaningful assessment can be made of the assumptions underlying the presentation of geochemical data in map form. Furthermore, the re-

TABLE 43.3. EXAMPLE OF ANALYSIS OF VARIANCE (ANOVA) MODELING OF GEOCHEMICAL DATA VARIABILITY; -250 MESH TILL DATE*, BEARDMORE-GERALDTON GOLD AREA, ONTARIO (after Closs and Sado 1981).

ELEMENT	GOLD	BORON	CHROMIUM
R	64	18	20
S	18	57	28
A	18	25	52
F1	S	S	NS
F2	S	S	S

R, S and A expressed as % of Total Variability

R = Regional; S = Sampling; A = Analytical

S = Statistically significant; NS = Not Significant at 95% confidence level

N = number of sites sampled in duplicate = 29

*Log 10 Transformed Data

sults help identify specific shortcomings in the project design and serve as a first step in the revision of procedures. For example: ANOVA results for gold, boron and chromium from a surficial geochemical program carried out in the Beardmore-Geraldton gold area of Ontario, Canada, are presented in Table 43.3 (Closs and Sado 1981). For this combination of sample type, sample fraction, and analytical method, the greatest proportion of the variability in the data for gold is resident in the regional component, which makes the abundance of gold a suitable parameter for mapping purposes in this area. The greatest proportion of the variability in the data for boron is resident in the field sampling component, which suggests that boron in the sample medium is unsuitable for mapping, and that improvement in the field sampling procedure is needed. The greatest proportion of the variability in the data for chromium is resident in the chemical analysis component, which suggests that this element is also unsuitable for mapping. The analytical procedure is the component requiring improvement in this instance.

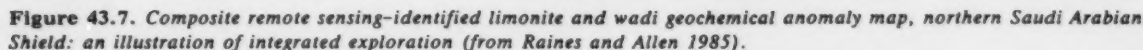
Traditional models used in exploration geochemistry provide a powerful means of assessing large amounts of data and of guiding overall project design. Methodological geochemical models are essential for assessing fundamental reliability of surveys and for guiding intelligent geological interpretation of results.

INTEGRATING GEOCHEMISTRY WITH OTHER EXPLORATION DISCIPLINES

Integrating geochemistry with other exploration disciplines can improve overall effectiveness and efficiency in exploration for mineral deposits. Integration may be direct, or through technology transfer. In many instances the integrative approach is synergistic; that is, the effect of the combined approach is greater than that of the sum of the effects of the individual techniques.

Technology Transfer

Technology transfer is a hallmark of applied science. Exploration geochemistry is an applied science. From the early adaptation of analytical techniques from agricultural sciences, to the present, technology transfer has been one of the central



means for advancing the contribution of geochemistry to mineral exploration.

ENHANCING AWARENESS AND APPRECIATION OF GEOCHEMICAL TECHNIQUES

Geochemical exploration was initially promoted as being quick, inexpensive, and easy. Perusal of the review papers in the field in Hood (1979), and Garland (1989) would quickly dispel that notion.

Initial descriptions of techniques as being either theoretical or practical tend to remain, despite changes in the operation of the technique and/or change in the nature of the problem being addressed. As an example, studies of fluid inclusions were largely thought to represent a type of analysis associated with theoretical investigations of mineral deposits. Work by Buchanan (1979) indicated that this type of analysis could have direct, practical input to the search for ore shoots along vein structures. In another example, the present essential role of geochemistry in exploration for gold has generated a stronger appreciation of sampling representativity within the exploration community. Techniques must be assessed in the context of a specific problem rather than some pre-existing impression. The problem solving process noted above provides a means of formally addressing this situation.

When alternative techniques are being evaluated for potential inclusion in an exploration project, each is at a unique point in its evolution. By definition, each is incomplete and imperfect. That condition should not prevent its inclusion if the technique can be demonstrated to be capable of making a contribution to the discovery of a mineral deposit. However, simple conceptual awareness of a technique, coupled with the acquisition of the necessary equipment will not assure successful application. All too often, the lack of appreciation of the considerable art and judgement required to successfully utilize the new approach results in failure. When success does not come, the erroneous conclusion may be drawn that the technique does not work. Unsubstantiated evaluations of this type retard the development of the technique. The application of biogeochemistry, vapor geochemistry, and geomicrobiology to exploration for precious metals in the western United States is currently suffering these growing pains. Considerable opportunities exist for exploration geochemists prepared to realistically assess these techniques. Again, the problem-solving process provides a means of achieving this objective.

DISCUSSION

COSTS

Available budget commonly constitutes the major constraint on design and planning of geochemical surveys. While this is a reality that must be accommodated, a clear distinction should be made be-

tween cost-effectiveness and cost-efficiency. Cost-effectiveness refers to conducting technically sound surveys and obtaining full value for the funds expended. In contrast, cost-efficiency refers solely to reducing the cost of the survey. Cost reduction at the expense of a technically sound survey design frequently results in the waste of all funds expended.

Bailly (1972) provided general guidelines for the justification of any exploration methodology:

"Use a given method only if it can truly give discriminant results, improving the knowledge of the mineral potential of the area, at a cost estimated to be not greater than the extra cost incurred at the next exploration phase if the method had not been used at all."

The focus is on contribution based on technical and economic considerations.

PLANNING AND SEQUENCING

This review has focused on techniques applicable to general design and planning of surveys. Operational survey design and planning are typically specific for individual programs. Hoffman and Thomson (1986) provide detailed flowcharts for the specific steps involved in geochemical soil surveys. These flowcharts could serve as examples for developing similar operational plans for other types of geochemical surveys. In addition, Hoffman's (1986a) guidelines for the writing of geochemical reports provide information for design and planning of surveys. Confirmation of geochemistry as a valid exploration approach for a specific program, followed by monitoring of analytical quality control and sampling representativity, are common elements of all surveys.

FUTURE TRENDS AND OPPORTUNITIES

The availability of low-cost multi-element geochemical data provides numerous opportunities for improving survey design. The expansion of information on geochemical associations and pathfinder suites will result in greater resolution in the identification of both currently known, and yet to be recognized types of mineralization over a range of survey scales. Furthermore, these data can contribute to the recognition and quantification of overprinting geochemical processes unrelated to mineralization that mask the responses of targets. Multi-element geochemical data thereby contribute significantly to fuller and more confident interpretation of data. As an example of this latter aspect, Hoffman (1986b) cited the use of data for calcium and manganese as a means of identifying organic-rich soils which may be the cause of false anomalies (Figure 43.8). This recognition permits improved screening of anomalies and more effective ranking for follow-up action.

Mineral deposits are known to be characterized by isotopic signatures. Exploitation of these signatures in routine exploration programs has not been possible owing to the high cost of isotopic analyses. The potential for low-cost routine isotopic data

through the development of analytical systems such as the inductively coupled plasma mass spectrometer (ICP-MS) (Date and Gray 1983) will provide opportunities to evaluate systematically the exploration potential of isotopic data.

The use of computers, especially personal computers, in data management, presentation, and interpretation will increase the utilization of expanding geochemical data bases (Garrett, this volume). The previous lack of cost-effective methodologies to integrate field observations with geochemical data has resulted in the under-utilization of this geological data base. In extreme examples, field observations were not obtained; accordingly the quality of the geochemical interpretations has suffered. Significantly improved capabilities for routine computer graphics will place greater emphasis on recording

adequate field observation. Hoffman (1986b) provides an illustration of the systematic integration of field observations and geochemical data (Figure 43.9).

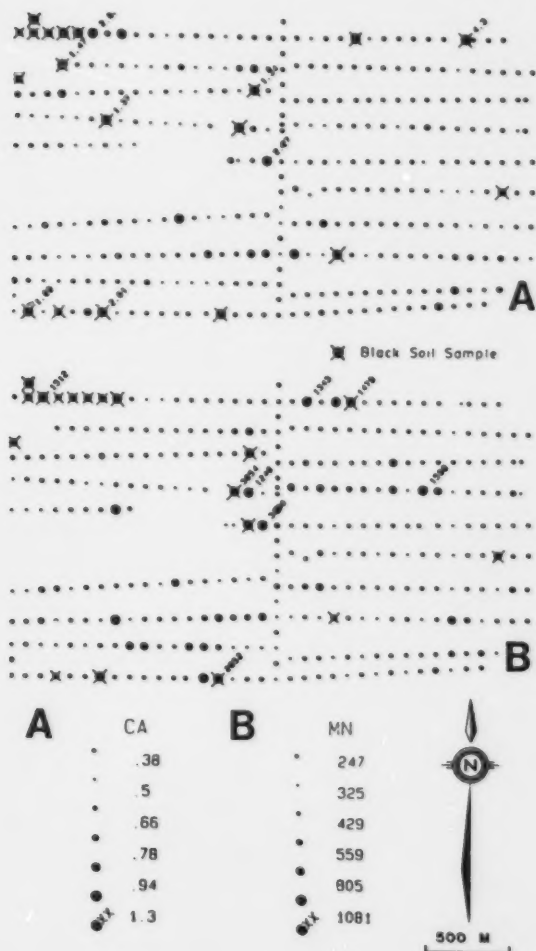


Figure 43.8. Illustration of the use of multi-element data to identify potential anomaly masking surficial processes. Here, Ca and Mn soil geochemical data used to identify organic-rich soils (indicated by "X"), a common source of false anomalies (from Hoffman 1986b).

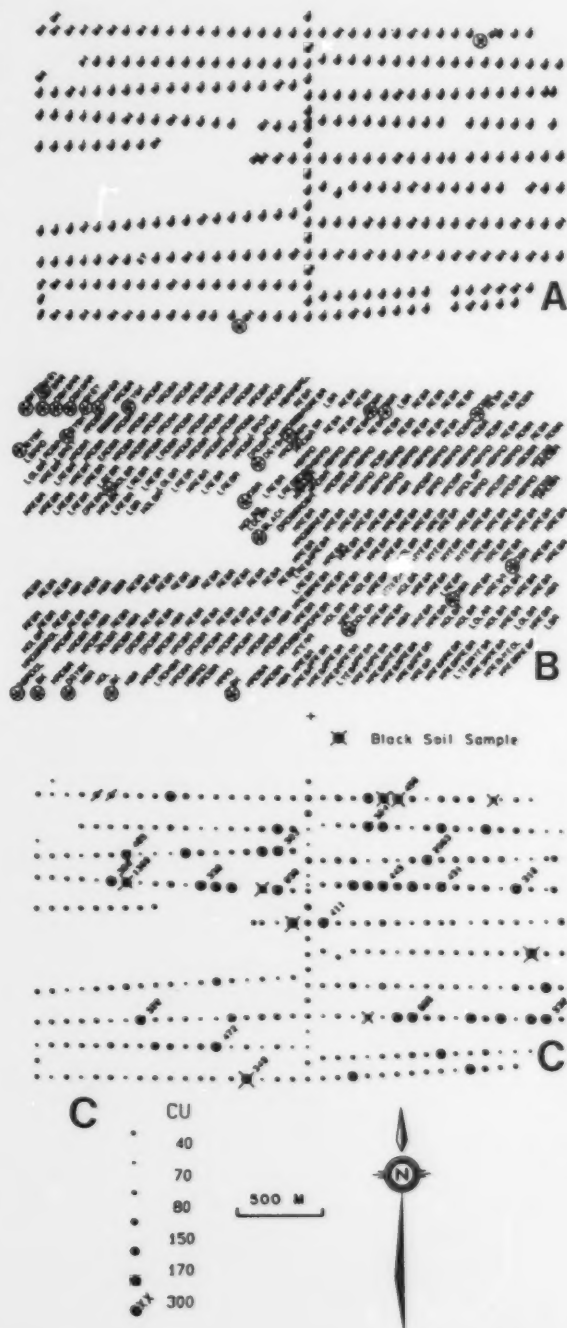


Figure 43.9. Illustration of the systematic integration of geochemical data and field observations via computer graphics (from Hoffman 1986b).

Over the past ten years considerable attention has been directed towards development of improved and expanded analytical and computer-processing capabilities. A backlog of methodologies now exists that needs to be evaluated. The question of sample representativity raised by current interest in the exploration for precious metals may apply equally well to other commodities. More attention must be focused on the field sampling and sample processing aspects of survey design and planning.

Attention should be directed toward improving project design and planning through systematic evaluation of alternative approaches to exploration based on more formal evaluation of contributions to discovery. Geochemical project design and planning has been addressed specifically in Christensen (1984) and Fletcher *et al.* (1986).

Finally, more emphasis must be placed on developing truly multidisciplinary programs in mineral exploration. Barriers between disciplines must be removed. Such emphasis will require change on the part of exploration personnel. A new type of explorationist is required, one who is able and comfortable with integration at both the technical and managerial level. Greatest hope for this change resides with industry because of organizational focus on a single goal. Design and planning are essential parts of the process, for an individual discipline, such as geochemistry, or for the exploration program as a whole.

SUMMARY AND CONCLUSIONS

The central challenge facing explorationists today is how to take full advantage of the sometimes bewildering array of alternative approaches available for consideration. The key to evaluating each opportunity is to focus on its contribution to discovery. The problem-solving approach emphasized in this paper provides a framework for such analysis. Rather than constraining creativity, as some believe, it provides focus so that greater advantage can be gained from creativity. Orientation surveys; modeling and models; purposeful integration of geochemical approaches with complementary exploration techniques and related disciplines; and increased awareness and appreciation of geochemical techniques and concepts amongst explorationists are means by which exploration geochemistry can expand its contribution to discovery and exploitation of mineral deposits. The process starts with the design and planning of surveys.

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44. Sample Preparation in Mineral Exploration

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ABSTRACT

Sample preparation is the sequence through which a field sample is reduced to a size suitable for analysis. The procedure may be accomplished by size reduction (e.g. crushing, grinding), physical or mechanical phase separation (e.g. gravity tabling, sieving, magnetics), splitting and blending. The final pulp must be representative of the bulk field sample and free of contamination from other samples and the equipment used.

Exploration-program materials typically prepared include rocks, ores, heavy-mineral concentrates, sediments, soils, humus, peat, vegetation and water.

The overall error (TE) in an analytical data set can be expressed as:

$$TE = FSE + SPE + AE$$

where FSE is the field sampling error, SPE the sample preparation error and AE the analytical error. The subject of this paper, the SPE term, can be further subdivided into sampling error (SE) and preparation error (PE).

In this paper we describe experimental procedures (minerological evaluations, sieve analyses, multiple analyses) and statistical approaches (GY's formulas, CLIFTON) used to develop optimum sample preparation procedures that ensure minimization of the SPE term and maximize analytical data quality. We also present typical sample preparation flow sheets for specific exploration targets (gold, PGM's, base metals).

45. Analytical Services for Mineral Exploration, a Review and Update

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ABSTRACT

Developments in analytical instrumentation over the past twenty years or so have progressively led the exploration geochemist out of an era in which a few carefully selected "pathfinder" elements were determined and data were plotted manually, into an era in which large multi-element analytical packages are the norm and a seemingly limitless number of computer programs are available to provide assessment.

A brief review of this progression and where it has taken us will be presented.

Specific attention will be given to modern instrumentation such as plasma spectrometers (ICP and

DCP), plasma mass spectrometers (ICP/MS), neutron activation (INAA) and X-ray fluorescence (XRF) and what may realistically be expected of these. Attention will be given to possible future developments.

Rapid, automated laboratory execution followed by electronic flow of data to the exploration geochemists P.C. is now routine. Despite this highly sophisticated analytical capability, its potential can only be realized with adequate communication, advice and discussion between the field geochemist-geologist and the analytical facility. This should allow selection of the optimum analytical procedures having regard for the nature of the field program.

46. The Role of Computers in Exploration Geochemistry

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ABSTRACT

The role that computing has assumed in exploration geochemistry for the period 1977 to 1987 has been assessed on the basis of a literature review, and to a lesser extent the personal experiences of the author. In the last decade, major changes have occurred in the computing environment. Microcomputers are now widely used in both the office and field. This has resulted in a significant increase in interactive computing, often accompanied with graphical capabilities, which has permitted geochemists to work more closely with their data. At the opposite extreme, supercomputers are becoming available to geochemists so that modeling and simulation problems previously considered intractable can now be solved. The new realm of expert systems and artificial intelligence is just beginning to be investigated in the context of exploration geochemistry. These techniques hold considerable promise as so many of the practical applications in mineral exploration are based on accumulated knowledge, "lore", and empirical or heuristic rules. The review concludes with a look forward to the next decade and identifies some areas where significant progress is likely.

INTRODUCTION

The period 1977 to 1987 has seen a rapid growth in the application of mathematical, statistical, and graphical procedures using computers to a variety of exploration geochemistry tasks and problems. The groundwork for much of this had taken place during the previous decade in research groups. The almost explosive growth of computer applications in the last decade has been largely due to availability of affordable computing power and better, more friendly and easy to use, software.

In 1977, the first microcomputers became available, the following year Apple introduced its model I machine, a little later machines using the generic CP/M operating system were widely available, and in 1982, IBM introduced its PC machine using the MS/DOS operating system. With that last event, half way through the decade we are considering, microcomputing became fully acceptable. The year 1978 was also marked by the introduction of the VAX 11/780 super-minicomputer by Digital Equipment Corporation. This machine, and similar ones supplied by other vendors, gave traditional large mainframe computing power to users at minicomputer prices. Much of the growth in acceptance of computing by exploration geochemists is due to the availability of

cheap computational power available through the generation of hardware introduced in the late 1970s. Over the longer period of 25 years since computers have been used by exploration geochemists, the cost of the same computing power has dropped three orders of magnitude, from four million dollars to four thousand dollars.

The subsequent sections consider exploration geochemistry computing activities under several topics, these are: data acquisition and data base activities, survey design and quality control, univariate statistics, mapping and spatial data presentation, multivariate data analysis, classification, resource appraisal studies, artificial intelligence, modeling, and microcomputers for geochemical data analysis. Finally, on the basis of the last decade's progress and today's computing technologies, some conclusions and thoughts are presented on where important advances may occur in the next decade.

Since the previous decennial review by Howarth and Martin (1979), several other books and papers of a review nature have been published. Readers may find these of interest in determining the role that computers have taken in assisting exploration geochemists over the last decade; Garrett, Kane, and Zeigler (1980), Cameron (1983), K. Campbell (1983), Garrett (1983a), Howarth (1983b), De Vletter (1983), Howarth (1984), Garrett (1985), Howarth and Garrett (1986), Hanley and Merriam (1986), and Siriunas (1987). Additionally, Howarth and Turner (1987) have published a revealing study of the use and misuse of graphical procedures in geochemistry.

DATA ACQUISITION AND DATA BASE ACTIVITY

Currently, computers are still dominantly being used for laboratory data acquisition rather than field data acquisition. Rugged microcomputers have been developed for field data acquisition in geochemical and soil surveys in Sweden and the U.K. (Clarke *et al.* 1986; Lundholm *et al.* 1986); however, their use does not seem to be widespread. More commonly computer and communications technology has been used in geochemical laboratories to automate data acquisition, track samples, assist in quality control procedures and compile data for geochemical samples derived by different analytical procedures. Little has been written concerning this work; however, in North America many large commercial and government geochemical laboratories use systems based on minicomputers. One commercial laboratory example

has been described by Blok (1986). An example of a low cost microcomputer based system, GLADD was developed in the early 1980s at the Geological Survey of Canada, Ottawa. GLADD uses a network of inexpensive CP/M based machines attached to analytical instrumentation that feeds data to a larger CP/M machine where quality control and data compilation is undertaken.

The availability of digital data has made it feasible for users to directly obtain their geochemical data from the laboratories where they are being generated by transmission over telephone lines. S.C. Smith *et al.* (1983) described such a system named CRAG. The growth in computer usage and advances in communications technology and computer networking are such that within the decennial review period digital communication of this type has gone from being a rarity to being routine.

Data bases in the 1960s and 1970s were usually considered to be major institutional resources. That has changed and now geochemists have access to sophisticated data base management packages, e.g. dBase III, Rbase System V and Oracle, on the microcomputers in their offices. Networks of data bases are emerging that are maintained to meet institutional and corporate objectives. The institutional data base is typified by the U.S. Geological Survey's RASS system (van Trump and Miesch 1977), and others have been described by Ferguson *et al.* (1977), Garrett, Kane, and Zeigler (1980), and Bliss (1986). A review of data base requirements for exploration geochemistry has been presented by Mattis (1983), and proposals for some standardization, particularly appropriate for those working on international cooperative studies, have been made by Grandclaude (1979). Often data bases are developed for a specific project by a small group of geoscientists. One such example which has been described as a case history concerns geological and geochemical data acquired for a project in Ethiopia (Davidson and Moore 1978).

Although geochemical data bases almost always include sample location coordinates, these are usually not manipulated at any other than a simple level, e.g. retrieve all samples that fall within defined limits. A new breed of specialized data bases known as geographic information systems (GISs) are now available. However, they are large and expensive, and all but a few require at least a minicomputer. Such information as maps may be stored in a GIS and retrievals such as: find all samples that are within 2 km of rhyolite-andesite contacts, are possible. Olson (1986) has described such a system running on a microcomputer, and several major geoscience institutions are purchasing or considering the purchase of such systems.

SURVEY DESIGN AND QUALITY CONTROL

The design of geochemical sampling procedures, i.e. the selection of sample densities, is not a topic that has drawn much attention. Various aspects of design selection criteria have been reviewed by Garrett (1983b), and a study by Garrett and Sinding-Larsen (1984) proposed criteria for the preparation of composite samples. In the latter study, it was demonstrated that cost considerations were more important in selecting composite sample sizes than statistical concerns in most instances. In an interesting paper by Shulman (1988), the problems of optimizing the entire exploration process are studied. The objective being to determine the optimal allocation of resources between geological, geochemical, geophysical, and other surveys.

Quality control procedures for geochemical analytical work have received far more attention. Of particular note is the graphical procedure developed by Thompson and Howarth (Thompson 1978; Thompson and Howarth 1978; Thompson 1983a, 1983b) and also described by Fletcher (1981). This procedure, based on plotting differences between duplicate analyses against the duplicate mean on a log-log display, is easy to implement and the display can be continuously updated in the laboratory so that any procedural problems can be rapidly detected and action taken. The simple model of a linear dependence of analytical error on concentration assumed by Thompson and Howarth may not always be true, as pointed out by Ottesen *et al.* (1983). This is due to changes in solute concentration or spectral line performance in the total range of concentrations being studied, brought about by the need for solute dilutions or line changes due to self absorbance phenomena. In such cases, several control charts can be prepared, one for each homogeneous concentration range.

The subject of reproducibility of geochemical surveys and the apportionment of variability between true geochemical, sampling and analytical factors has not received much interest. The reasons are most likely that, firstly, most mineral explorationists believe they are looking for "anomalies" that are so large they will be detected anyway, and secondly, they are not prepared to bear the cost of the additional sampling and analysis required to quantify the variability. An effective and economic method for determining survey variability was described by Garrett and Goss (1979) who employed an unbalanced sampling design for studying lake sediment survey data. In an attempt to determine after the event how effective a geochemical survey may have been at detecting patterns related to mineral deposits, Garrett and Goss (1980) employed the variability measures to modify the estimates of probability of intersecting

a pattern of known size based on geometric probability. The empirical model performed acceptably and was used to determine the probable effectiveness of the lake sediment surveys of Canada's Uranium Reconnaissance Programme. James and Radford (1980) described a simple procedure employing duplicate sampling and analysis to determine the relative magnitude of sampling and analytical variability in relation to total survey variability. They concluded, as many others have done, that today in most instances sampling variability is of far more concern than analytical variability.

UNIVARIATE STATISTICS

In reviewing activities over the last decade, one might be led to believe that little progress has been made. However, although relatively few papers have been published compared to those dealing with mapping and multivariate techniques, some are important contributions. The following section is divided into three topics, data transformations, anomaly recognition, and miscellaneous.

Transforming data to normality so that the assumptions of a variety of statistical methods might be met received a lot of attention in the early part of the decade. Kane (1979) proposed the use of a three-parameter lognormal distribution, where in addition to the mean and variance a shift parameter, α , was applied to the data. Thus a value x was replaced by $x + \alpha$, and α was estimated using a maximum likelihood procedure. As the value of α approaches zero, the familiar two-parameter lognormal distribution is obtained. Almost simultaneously, Howarth and Earle (1979) introduced the Box-Cox generalized power transform into geochemical use. Here the value of a parameter, λ , is estimated for a transformation, $z = ((x + \alpha)^\lambda - 1)/\lambda$, such that the skewness of the transformed variable z is minimized. The shift parameter α is chosen so that $x + \alpha$ is always positive; if x is never negative, α is set to zero. The values of λ may assume a continuum, e.g. -1, representing $1/x$, through zero where $z = \log x$ to 0.5 corresponding to $\sqrt{x}$ and 1 where z represents x and finally to 2 where z represents x^2 . This method is extremely powerful and examples of its use are provided by Howarth and Martin (1979) and Mancey and Howarth (1980), both in the context of multivariate data analysis procedures. However, if this procedure is applied routinely, problems can arise. For instance, if a data set is in fact drawn from an underlying normal distribution but also contains some erratically high values drawn from some other distribution(s), i.e. potential geochemical anomalies, the Box-Cox generalized power transform in attempting to consider the data as being drawn from a single distribution will generate a value of λ indicating a positively skewed, possibly lognormal, distribution. In the light of our *a priori* knowledge, this is clearly not correct and herein lies the problem with

routine use of such powerful transformation procedures. In recent years, it has become more common to use robust statistical procedures and select a model, e.g. normal or lognormal, on *a priori* geochemical grounds. Robust statistical procedures (e.g. Garrett *et al.* 1980; Campbell 1984) give less weight to outlying members of the data set and base the parameter, i.e. mean and variance, estimation on the core data. A clear trend over the decade has been a decreased use of means and standard deviations due to the conceptual problems over distribution models and multiple populations. In their place, medians and various percentiles are being used, having the advantage that they are distribution-free. Additionally, the median is a stable resistant estimator for the central tendency of data. Although percentiles are more tedious to estimate as the data have to be sorted, this is no longer a problem now that computers are widely available. However, for very large data sets special algorithms are required (Howell 1983).

The prime task in geochemical data interpretation still remains anomaly recognition and threshold selection. This topic has continued to be one of major interest and discussion (e.g. Garrett 1984). The procedure for cumulative frequency plot decomposition forwarded by Sinclair in the 1970s was "computerized" by Bridges and McCammon (1980). The great advantage of this was that the user could quickly try out a number of decompositions and observe the effects of any changes in input parameters, or number of populations, on the ultimate outcome in an interactive computer graphics environment. A limitation of the Sinclair, and Bridges and McCammon procedures is that only a single distributional type can be worked with at a time, e.g. all normal or lognormal subpopulations. Additionally, Campbell (1984) had pointed out and demonstrated the problems that can arise with numerical solutions to frequency decomposition when outliers are present, and proposed the use of robust procedures to solve this problem. Bjorklund (1983) demonstrated a number of situations where the anomalous population was more likely to be exponential, and discussed the impact of this on decomposition procedures. The impact of very skewed distributions on anomaly recognition procedures has also been discussed by Ingamells (1981). Ingamells demonstrated the impact of the nugget effect giving rise to a relatively small number of extremely high values for elements dispersed in discrete element-rich mineral grains and how this in part could be due to sample preparation variability.

An alternative procedure has been investigated by Miesch (1981) and Stanley and Sinclair (1987b). Instead of focussing on linear sections of a probability plot, the transition regions of sparser data density between the linear sections are studied. A gap test was proposed to determine if the data were sparse enough to be the upper and lower tail area of two

distributions. If such was the case, the data could be subdivided and the two populations interpreted in the light of local geological and geochemical knowledge. The method may be thought of as a one-dimensional cluster analysis, and would seem to be particularly appropriate where there is limited overlap between adjacent populations. Cole and Rose (1984) proposed the use of a Student's *t*-test to determine whether two identified groups of data could in fact be considered as drawn from two populations, or should be considered as a single population.

Li (1984, 1985) took a different approach by simultaneously taking spatial information into account in an analysis procedure developed to subdivide data sets into their component parts. The result of this approach is that when a post-analysis map of the populations is prepared, it is "cleaner", border line cases being grouped into the population which is locally dominant. Page and Young (1981) have used spatial clustering to determine the significance of "anomalous" samples. If a threshold is set that identifies the top 5 percent of the data and the "anomalies" were just high level background samples, one would expect them to be scattered randomly over the survey area. The probability of these anomalies lying together as contiguous groups can be determined for various group sizes. Intuitively, the larger the group the less likely this is due to chance alone and the more likely the group is related to a discrete geochemical cause. Page and Young's approach is based on binomial theory and therefore has the attraction of being assumption free concerning the underlying geochemical distributions.

Several other papers are of note. Cameron (1983) and Sinclair (1983) both provided useful reviews of univariate statistical procedures applied to exploration geochemistry. In a recent paper, Stanley and Sinclair (1988) discussed the bridge between univariate and multivariate procedures. Often this involves using a multivariate procedure to determine a univariate measure related to the process under study, and then using univariate procedures on that derived measure. Andrew (1984) provided examples of univariate procedures in anomaly recognition, extending into the bivariate and multivariate realms, emphasizing the multivariate nature of most geochemical data. Finally, although geochemists usually collect field data at the sample site, traditionally used to reconstruct the sample site environment during detailed interpretation, rarely have the field data been subjected to detailed analysis. However, Matysek *et al.* (1983) analyzed field data from a British Columbia stream sediment survey and showed the results to be consistent with the geochemical data and useful in support of data interpretation.

MAPPING AND SPATIAL DATA PRESENTATION

The geochemical map is a fundamental tool to the exploration geochemist; the past decade has seen a continued growth of computer use to aid map preparation, and more importantly the adoption of new procedures, e.g. image analysis systems. The subject will be reviewed in three sections concerning contouring and interpolation algorithms, the application of image analysis approaches, and miscellaneous new developments and the use of colour. Additionally, Howarth (1983a) has reviewed mapping and data presentation techniques.

One of the first computer procedures used by geochemists to prepare contoured maps in the 1960s was polynomial surface fitting, often called trend surface analysis. The procedure is still being used, for example in papers by Chapman (1978), Ganicott *et al.* (1979), Mercree *et al.* (1979), Yu (1981), Pride and Hasenhohr (1983), and Roy (1983). However, with time these techniques seem to be used less and less. An interesting variant has been described by Bezvoda *et al.* (1986) who used a fitted Fourier model to describe the spatial variability of soil geochemical data. Most contouring today is undertaken using local fitting or filtering, and these techniques break down into two groups: firstly *a priori* based procedures, e.g. inverse squared distance weighting, or secondly, data-based local weighting, e.g. kriging based on autocorrelation (variogram) studies or some similar procedure. Howarth *et al.* (1980), Sarma and Koch (1981), and Chork and Cruikshank (1984) have shown that by fine tuning filters applied to spatial data different features can be highlighted to advantage. An interesting study by Myers *et al.* (1982) and Kane *et al.* (1982) compared a procedure for determining the optimum parameters of a filter, i.e. the power applied to the spatial distance measure and the search radius, with an autocorrelation study. By comparing interpolated results at validation points with observed data, they determined that, for their particular geochemical groundwater data set, kriging generally provided an inferior map to that obtained using optimal inverse distance weighting model. This conclusion may be due to non-stationarity in the regional data set. This property of the data is likely a reality in regional geochemistry, and may be the reason that kriging does not always provide acceptable regional geochemical maps. Unfortunately, testing for and handling non-stationarity is difficult (Henley 1981). Bonham-Carter and Goodfellow (1984) undertook an autocorrelation study of regional stream sediment survey data from the Northern Canadian Cordillera. In this work, they demonstrated that the spatial correlation in the data was due to the geology of the area, and that if the data were adjusted for local geologically controlled geochemical background, they were not

significantly spatially correlated. As a general rule, it seems likely that for large regional geochemical survey data sets with broad sample spacings spatial correlation is more closely related to differences in local lithology and the autocorrelation due to the geometry of the geological units than to any internal spatial variation patterns within lithologies. It is interesting to speculate as to whether this observation will hold true on the scale of continental geochemical map compilations where major crustal scale phenomena may exert a control on regional geochemical background in a systematic way.

Kriging procedures have been used to prepare regional geochemical maps, e.g. Armour-Brown *et al.* (1983), Bonham-Carter and Chung (1983), Lindquist *et al.* (1987), Muge *et al.* (1987), Sandjiv (1987), and Wackernagel and Butenuth (1987), or as an intermediate step in moving from an irregular pattern of geochemical data sites to a regular grid as required by an image analysis system, e.g. Bolivar *et al.* (1983). However, more commonly autocorrelation studies and Kriged maps have been applied on a local scale where the true distance related spatial variability in the data is not overwhelmed by differences related to lithologically controlled backgrounds. Examples of the more local studies, often applied in the multivariate context can be found in the work of Royer (1984, 1988), Sandjiv (1984, 1987), and Grunsky and Agterberg (in press). The proximity analysis approach of Royer is a logical extension to the formal inclusion of spatial information in a statistical analysis framework.

It has been long recognized that numerical interpolation and contouring procedures have caused problems when applied to drainage basin samples on a local scale. Quite simply, the coordinate stored is that of the sample site, not the centre of the area that the geochemist considers the sample to represent. Earle (1978) made an attempt to solve this problem by associating each stream drainage site with a sector of defined radius, orientation, and arc. In retrospect, Earle was ahead of his day as graphical data-acquisition procedures of that time rendered the procedure of academic interest only. The availability of optical scanners has made it possible to directly capture the geographic coordinates defining the boundary of a drainage catchment basin (Ellwood *et al.* 1986; Aronof *et al.* 1986; Los Alamos National Laboratory *et al.* 1987). With the digital cartography and image analysis procedures now available, a totally new approach can be taken to geochemical map presentation, as colour or a grey-scale coded polygon can be used to indicate the actual area represented by each geochemical sample.

The impact of image analysis systems is now beginning to be felt, especially as lower-cost micro-computer-based workstations are becoming available. The power of an image analysis system lies in its ability to manipulate maps as digital images. In

addition to geochemical maps, they may include satellite imagery (e.g. Aronof *et al.* 1986), geological maps (e.g. Bolivar *et al.* 1983), and geophysical maps (e.g. Guinness *et al.* 1984). It is the data integration aspect that makes image analysis so attractive, and there are now many examples of this. The first attempts at data integration included work that was not carried out on a true image analysis system, e.g. Bonham-Carter and Chung (1983), followed shortly by the more elegant colour-based systems, e.g. Green (1984), Leymarie and Durandau (1985), Fettes *et al.* (1986), Aronof *et al.* (1986), Plant *et al.* (1986), Maassen and Bolivar (1987), and Las-serre *et al.* (1987). Perhaps one of the most interesting of these is the work of Aronof *et al.* (1986) where stream sediment and water data and geological information were combined to undertake a tungsten mineral resource appraisal. Other noteworthy work is that by Plant *et al.* (1986) where clarification of a number of outstanding problems in Scottish geology has been obtained from geochemical mapping. An interesting alternative has been pursued by Bolivar *et al.* (1983) and Freeman *et al.* (1983) where they used multivariate procedures to combine the geochemical data into new variables prior to integrating it with the geological data using an image analysis system.

Due to the availability of colour devices in both large and small formats for computers, the use of colour is becoming more widespread. However, much of this use is during data interpretation and is never published due to high printing costs, though it is noticeable that journals are more willing to publish colour figures now than 10 years ago. The paper by Reid (1987) on primary tin dispersion provides an example of colour graphics in the interpretation role. Colour maps are now being published at either page size, e.g. Friske (1985), Bjorklund and Gustavsson (1987), and Maassen and Bolivar (1987), or in larger formats in geochemical Atlases, e.g. Webb *et al.* (1978), Weaver *et al.* (1983), Bolviken *et al.* (1986), and Los Alamos National Laboratory *et al.* (1987).

There have been a number of proposals for new methods of mapped data presentation in addition to those described above. Fortescue (1981, 1983) and Fortescue *et al.* (1982) proposed a greater use of maps where the data is ratioed against a crustal abundance estimate, e.g. the Clarke. These maps have particular appeal to health and environmental studies, where the maps are being used in epidemiological studies. In such cases, users are not interested in absolute values but differences from a norm, mainly for spatial correlation with areas where population statistics indicate increased longevity or mortality. Bjorklund and Gustavsson (1987) discussed methodology behind certain of the maps used in the Geochemical Atlas of Fennoscandia (Bolviken *et al.* 1986). In light of a recent proposal to the International Geological Correlation Programme

that geochemists cooperate internationally to prepare a global geochemical map series, their introduction of moving median maps as the best stable measure of regional background geochemistry may have particular importance.

MULTIVARIATE DATA ANALYSIS

In comparison with other branches of geoscience, exploration geochemistry has been a centre of multivariate data analysis, no doubt due to the abundance of multi-element survey data. To aid discussion of the large body of literature generated in the last decade, the review is divided into seven topics as follows: closed numbers, bivariate procedures, clustering, regression, principal component and correspondence analysis, discriminant analysis, and miscellaneous topics of interest. Underlying many of the applications of multivariate statistics to exploration has been a desire to classify individual samples, or at least identify those that may be considered "anomalous", on the basis of some objective criteria (Garrett 1984; Mellinger *et al.* 1984). During the review decade, several papers have been published which treat the role and potential of multivariate data analysis from a more general point of view, i.e. Chapman (1978), N.A. Campbell (1983), Garrett (1983a), Howarth and Sinding-Larsen (1983), Howarth and Garrett (1986), and Mellinger (1987a).

Exploration geochemists working with whole-rock data and petrochemists have long been aware of the problems arising from the fact that major element analyses sum to a constant, 100 percent. Therefore, as a major component increases, say silica, other components necessarily decrease, and studies of intercomponent variability using correlation measures have not always been satisfactory. Trace-element geochemists have been far less concerned with these problems, and it is now known on theoretical grounds that the commonly used log-log plots of trace elements are not affected by the closure problem. Hohn and Nuhfer (1980) proposed a procedure for computing true correlation coefficients unaffected by closure through the use of ratios involving the major component. For example, instead of computing the correlation of Fe and K, the correlation of Fe and $K/(100 - Si)$ was computed; and for K and Fe, the correlation of K and $Fe/(100 - Si)$ was derived. The problem with this procedure is that the correlation of K with Fe is not the same as Fe with K, and where the range of a variable is large, e.g. Si, the correlation of Si with $Si/(100 - Si)$ may not be equal to 1, which is intuitively unsettling. The breakthrough in this area was made by Aitchison (1981), and in two later papers (Aitchison 1984a, 1984b), when he proposed the use of the logistic transform, all this work is reported in Aitchison (1986). If there are $d + 1$ components that sum to a constant, e.g. 1 or 100, each of the d

values are divided by the $(d + 1)$ -th and logs are taken. The new transformed variables do not exhibit the closure effect and any correlations between them reflect true correlations due to geochemical processes. The selection of the $(d + 1)$ -th component is not critical, and therefore with whole-rock geochemical data oxides such TiO_2 or ZrO_2 are often chosen on the basis of common petrochemical practice. Therefore, the plotting of K_2O/TiO_2 versus Fe_2O_3/TiO_2 on a log-log scale reveals correlations that are truly geochemical. This does not mean that the old Harker diagram approach of direct elemental plots is obsolete; they are useful in the study of classification due to the enormous mass of historical data so plotted; however, they have no place in the study of geochemical processes. Butler (1981) carried out studies along a different line, however, Woronow and Butler (1986) later adopted Aitchison's logistic transform and published computer software for testing for the presence of true independence in close arrays. Royer (1983) proposed the use of correspondence analysis as a solution to the closed number problem, and the relative merits of correspondence and principal components-factor analysis will be discussed in a later section.

The simplest form of multivariate data are bivariate data sets, or true multivariate data treated pairwise. Two different approaches have been taken with pairwise data to reduce the effect of outlying individuals which influence the estimation of lines-of-fit or correlation coefficients. Rock (1986) and Rock and Duffy (1986) have encouraged the use of non-parametric or assumption-free methodologies. In contrast, others, e.g. Zhou (1987), Wurzer (1988), and a procedure described by Rock and Duffy (1986), have preferred to remain with the more common parametric procedures and modify them to downweight the influence of outlying individuals. Wurzer (1988) proposed the use of influence functions displayed directly on bivariate plots to assist in the identification of outliers that might effect the statistical estimators. Examples of bivariate data analyses are found in the work of Gibbs (1982) to study Cu versus Fe or Mn in tropical stream sediments; Garrett (1983a) to investigate Zn-Fe relationships in temperate zone stream sediments; Andrew (1984) used bivariate plots to aid in anomaly recognition; and Drew *et al.* (1985) studied a variety of combinations of Cu-Ni data to differentiate between stratigraphic zones in the Stillwater ultramafic complex.

Cluster analysis procedures offer a very useful tool with which to commence the investigation of large or complex data sets in order to disaggregate the mass of data into several smaller more tractable subsets. These subsets are likely to be composed of individuals dominated by particular geological or geochemical processes, perhaps even related to a mineralization process, and may then be further

treated by the most appropriate methods. There are two specific approaches to cluster analysis, one is hierarchical and commonly uses dendrograms, and the other is non-hierarchical and often referred to as a k -means or partitioning method (Howarth and Sindling-Larsen 1983). Examples of the use of dendrograms may be found in Ayalon *et al.* (1981), Roy (1981), Yu and Xie (1985), and Hoffman *et al.* (1987). The work by Yu and Xie (1985) is particularly interesting as they take account of the "fuzziness", i.e. uncertainty, due to natural and measurement variability in their analysis. Jambu (1981) proposed an interesting hierarchical procedure for use with large data sets, however, Mancey (1982) in a review of clustering procedures for large geochemical data sets states a preference for non-hierarchical methods. Examples of these may be found in the work of Lefebvre and David (1977), Dumitriu *et al.* (1980), Mancey (1982), Garrett (1983a), Granath (1984), Chork and Govett (1985), Grunsky (1986), Kurzl (1987), and Shepherd *et al.* (1987). Garrett (1983a), Chork and Govett (1985), and Kurzl (1987) used assumption-free planing or non-linear mapping procedures. Gustavsson (1980, 1983) also made use of a graphical clustering procedure, the Andrew's plot. In these graphical procedures, the user makes the partition on an x - y plot of the multi-dimensional data, rather than relying on a partitioning algorithm, which commonly breaks down when single outliers are encountered. Both Lefebvre and David (1977), and Grunsky (1986) have used a procedure known as dynamic cluster analysis to advantage with petrochemical data. By employing the concept of clouds of points, the aspect of data fuzziness is introduced where a group of data is not characterized by a single so-called "typical" sample, or a "typical" composition not reflected in any individual, but by the statistical properties of all the individuals in the group. A particularly interesting facet of this procedure is the method used to determine the true number of clusters in a data set and how after repeated trials persistent sets of data groupings are identified. Granath (1984) proposed a k -means procedure which also takes data fuzziness into account; this method is potentially very powerful but has the drawback of being computationally intensive. However, with new computing tools this drawback will disappear. One drawback with cluster analysis procedures is that they usually illustrate the data variability in either the variable space (R -mode) or sample space (Q -mode). Therefore, one can determine which samples are similar but not why, i.e. which variables provide them with a unique fingerprint. One of the few procedures that can achieve this are Kleiner-Hartigan trees, these were used by Garrett (1983a) and indicated the complexity that even a small data set can attain. Like the planning and non-linear mapping procedures, it is the user who groups the trees into "groves" of similar morphology and/or size. As a generalization, it would appear that partitioning procedures, whether

algorithmic like k -means or graphical, are becoming the methods of choice in exploration geochemistry in preference to dendrograms.

Regression analysis has a long history of application to geochemical exploration data back to the 1960s. The objective in these studies has been to develop models of trace-element background in terms of other trace elements, the major elements dominating geochemical composition, and geology. The inclusion of geological information in regression analysis has commonly been via 0 - 1 dummy variables indicating the presence or absence of the lithologies or formations of interest, e.g. Whitney (1981), Bonham-Carter and Goodfellow (1986), and Bonham-Carter *et al.* (1987), or by subdividing the data into subsets on the basis of geology, e.g. Koch *et al.* (1981). Of note recently has been the use of the actual proportion of a geological unit comprising a drainage catchment basin by Bonham-Carter and his co-workers; however, Bonham-Carter *et al.* (1987) still recorded the presence of geological contacts considered important in the analysis with 0 - 1 dummy variables. The very outliers being sought when regression models are being used to identify them can distort the analysis and render it ineffective. Therefore, a number of workers have used robust and/or iterative procedures to remove the influence of the outliers and so generate improved geochemical background estimates. Garrett *et al.* (1982) and Zhou (1985, 1987) both used robust estimators for the means and covariances required by the regression analysis, whereas, Malmqvist (1978) and Stanley and Sinclair (1987a) both used iterative procedures to eliminate influential outliers from their analyses. Other examples of the application of regression procedures can be found in the work of Price and Ferguson (1980), de Vivo *et al.* (1981), Capaldi *et al.* (1982), Bonham-Carter and Chung (1983), Howarth *et al.* (1981), Dubov (1983), Rose *et al.* (1983), Selinus (1983b), and Wynne and Strong (1984). An interesting variant for estimating local backgrounds in large multivariate data sets probably drawn from multiple populations is presented by Roquin and Zeegers (1987). Instead of using the total data set to estimate the expected value for an individual under study, they used only a subset of data from the multivariate data space close to the individual to be estimated. This means that as many regression models have to be computed as there are individuals in the data base. Although several years ago this would have been a daunting task, with today's computing power, either a supercomputer in seconds or geochemists' microcomputer running overnight, it no longer poses a problem.

For some 20 years it is reasonable to say that principal components-based approaches, joined by correspondence analysis about 14 years ago, have been the most popular multivariate data analysis techniques. Their lure is in their ability to re-express

the data variability in terms of geological or geochemical process rather than raw elemental compositions. Like cluster analysis, principal components and factor analysis may be undertaken in either the *R*- or *Q*-mode. Since the implementation of the *RQ* transform procedure in the early 1970s, the analyses have become interchangeable; there does however appear to be a preference for using *R*-mode scores rather than *Q*-mode loadings due to users preference for interpreting the *R*-mode inter-variable loadings in terms of geochemical processes. Correspondence analysis has always been carried out in the *RQ* domain. A brief note must be made concerning principal components and factor analysis as the terms are used interchangeably by many. In practice, both are usually carried out on the data correlation matrix, however, the assumptions are different and in a practical sense a user commits to a factor analysis once a rotation procedure, e.g. using the Varimax criterion, is undertaken. In components analysis, the new axes are computed to explain a maximum amount of the original variance, in factor analysis the new axes maximize the correlation of the variables. Useful discussions of this with illuminating examples may be found in Chayes and Trochimczyk (1978), Trochimczyk and Chayes (1978), and Miesch (1980). A similarly very useful paper focussing on the differences between principal components and factor analysis on one hand and correspondence analysis on the other has been presented by Zhou *et al.* (1983). In the past decade, there have been two reviews of multivariate procedures in exploration geochemistry which discuss these procedures in some detail, Chapman (1978), and Howarth and Sinding-Larsen (1983). The examples of the use of *R*-mode principal components and factor analysis by geochemists are many, and include Barbier and Wilhelm (1978), Santos-Oliviera (1978), Olade *et al.* (1979), Tripathi (1979), Leach *et al.* (1980), Ajayi (1981), Dunn (1981), Selinus (1981), de Vivo *et al.* (1981), Capaldi *et al.* (1982), Imeokparia (1982), Bolivar *et al.* (1983), K. Campbell (1983), Davenport *et al.* (1983), Selinus (1983a), Olorunfemi (1984), de Vivo *et al.* (1984), Eleuze and Olade (1985), Nurmi (1985), Vriend *et al.* (1985), Bezdova *et al.* (1986), McConnell and Batterson (1987), Sharp and Nardi (1987), and Smith *et al.* (1987). All of these workers have used *R*-mode analysis procedures to support their interpretations, in some cases the results are used to confirm an already developed interpretation, and in others the analysis plays a more important role. A number of other authors have proposed new or modified procedures of more interest. The most frequently used rotation procedure applied during *R*-mode analysis is the Varimax, which is an orthogonal rotation and leaves the factors uncorrelated. Leymarie and Frossard (1983) proposed an oblique rotation for use with petrochemical data and found it aided their interpretation. Olesen and Armour-Brown (1984) used *R*-

mode residual scores to identify individuals whose variability could not be explained by the *R*-mode factors they selected as representative of the major controlling geological-lithological processes; a generally similar approach has also been employed by Esbensen and Steenfelt (1987). These are elegant procedures and can be likened to focussing on individuals that exhibit large regression residuals from a satisfactory background model. Both Zhou (1985, 1987) and Wurzer (1988) have proposed using robust estimates of the data set means and covariances (correlations) as a starting point for analysis. The resulting downweighting of outliers leads to a far better estimation of factor loadings reflecting the background geochemical processes, and the better resolution of background models itself leads to an easier recognition of "anomalies" different from the background(s). Lindqvist *et al.* (1987) presented work on a procedure named SIMCA which includes a partial least square approach where different variable sets, e.g. major and trace elements, or trace-element and geophysical parameters, are separately analyzed in *R*-mode and then related to each other in order to identify common factors controlling the variable sets. This procedure has been particularly useful in integrating data sets concerning the same individuals but of disparate nature, e.g. geochemistry, geophysics, mineralogy, etc. Finally, in *R*-mode analysis Royer (1984, 1988) and Sandjivy (1984) have both attempted to take the spatial context of data into account during factor analysis. Sandjivy (1984) proposed a procedure called factorial kriging analysis, the main drawback is that for large data sets it is extremely computationally intensive. Royer (1984, 1988) proposed an alternative, proximity analysis, which he states to be less of a computational task. However, with reference to both techniques, the interpretation of the results is more complex than in the routine *R*-mode procedures now so widely available in computational packages. On this basis, widespread application of these spatial techniques is unlikely in the near future.

Q-mode approaches are now rare, the most notable work has been by Miesch (1979) in interpreting petrochemical data in terms of sample vectors representing specific mineralogical compositions. This permits the results of the analysis to be interpreted as petrological mixing models. Correspondence analysis is routinely used in a similar fashion to *Q*-mode factor analysis, as evidenced by the plots of individual samples in the factor space. Much has been made by some workers of the ability to plot the variables on these same diagrams. However, this is not unique to correspondence analysis and biplotting has been available through the commonly used *RQ* transform procedure since the early 1970s. In a series of papers by Valenchon (1982, 1983) and Miesch (1983), various aspects of the factor analysis-correspondence analysis relationship are discussed. In a paper by Grunsky (1986) where corre-

spondence analysis is used to study petrochemical data, the author also discussed the relative merits of the two procedures; and Zhou *et al.* (1983), as mentioned earlier, discussed the mathematical relationships. Examples of the application of correspondence analysis to geochemical problems have been published by Durnitriu *et al.* (1979) and by Mellinger (1984, 1986, 1987b, 1987c) in addition to the previously cited authors. In the author's opinion, the strength of correspondence analysis is its ability to handle binary, e.g. presence-absence, data (Mellinger 1984; Mellinger *et al.* 1984). Correspondence analysis requires that the data be regarded as a contingency table or probability distribution, many geochemists are not particularly comfortable with this assumption. It seems to the author that now the closed number (constant sum) problem has been solved and that correlation matrices may be computed that reflect the true underlying geochemical processes that *RQ* factor analysis procedures have a lot to offer where constant sum geochemical data are being analyzed.

Factor scores, however computed, have the attraction that they combine data for multiple elements and re-express them in a manner that is more process than response related. If only a small proportion of the data is related to a particular process, as with mineralization processes in a regional reconnaissance survey, it may not be reflected well in a formal "factor" analysis. Several workers have used multi-element scoring procedures to aid in focussing attention on individuals associated with particular trace-element patterns, often selected due to an association with a particular mineral deposit type. Some procedures lead to an "empirical factor score", e.g. the weighted sums of Garrett *et al.* (1980), whilst others lead to a simple additive score, e.g. Smith and Perdrix (1983). In addition to the above two papers, examples may be found in the work of Marsh and Cathrall (1981), and Chaffee (1983). A slightly different approach has been proposed by Mellinger (1983) in a procedure he calls "Tails Analysis", the work of Skvortsov *et al.* (1982) appears to also follow a similar thrust, and Baird and Dennen (1985) offer an alternative procedure with a similar objective of focussing on "anomalous" multi-element patterns. Finally, it may be noted that the image analysis procedure used by Aronof *et al.* (1986) to generate a tungsten mineral potential map can be viewed as a graphical image combinatorial analogue of the numerical scores. These heuristic procedures may lack the formalism of a *RQ* mathematical procedure, but they gain by their direct geochemical motivation, in which lies their strength.

CLASSIFICATION

Traditionally, exploration geochemists have used various forms of linear discriminant analysis to clas-

sify unknown individuals into one or more populations. However, in the last decade other techniques have become available based on slightly different approaches. Two are of particular note, firstly, logistic regression, and secondly probabilistic modeling. Logistic regression is a particular regression procedure where the dependent variable is set to 0 or 1 for two data sets, e.g. background and mineralization associations. Maximum likelihood procedures are used to determine the coefficients of the independent (geochemical) variables in the regression model. The major advantages are two-fold, there are no assumptions of multivariate normality and homogeneity of covariance for the two data sets, and the results, i.e. estimated values of the dependent variable, are directly interpretable as pseudo-probabilities of group (data set) membership. The problem of homogeneity of covariance is often neglected by non-statisticians, however, homogeneity is an assumption of the simple linear discriminant method. In many cases in exploration geochemistry the assumption is probably not warranted. For example, in a background area Pb might be negatively correlated with Zn due to a negative correlation of feldspathic (Pb richer) minerals with dark (Zn richer) minerals, but be positively correlated in a mineralized zone due to the presence of sulphides. In such a case, the assumption of homogeneity of covariance is clearly not warranted. Probabilistic modeling can be likened to a multivariate probability plot where an individual is viewed in the light of one or more control populations. The individual's probability of group membership in that group is determined via its Mahalanobis distance, which can be regarded as a multivariate analogue of the familiar univariate standard normal deviate (N.A. Campbell 1983; Garrett 1987). This procedure has an advantage in regional surveys where very often although background populations are abundantly represented, the "anomalous" ones of interest are not. Therefore it is a useful strategy to characterize the background population(s) reliably and look for individuals that do not fit (c.f. Olesen and Armour-Brown, 1984). During the last decade two reviews of a more general nature have been published that discuss classification procedures and/or discriminant analysis, Chapman (1978), and Howarth and Sinding-Larsen (1983). Simple linear discriminants have been used by Santos-Oliviera (1979), Marcotte and David (1981), Pirie and Nichol (1981), Amor and Nichol (1983), Brabec (1983), Selinus (1983a), Andrew (1984), Wynne and Strong (1984), Chork and Govett (1985), and Shepherd *et al.* (1987). A common problem encountered in discriminant analysis studies is the selection of the most appropriate variables. One may rely on geochemical common sense and select ones known *a priori* from previous work to be good discriminators; use various exploratory data analysis approaches; use factor scores which are linear combinations of the elemental data, selecting the factors that contribute most useful information to the prob-

lem (c.f. Selinus 1983a); or use a stepwise variable selection procedure. The stepwise procedure has been used in studies by Beauchamp *et al.* (1980), Fedikow and Turek (1981), Clausen and Harpoth (1983), and R.E. Smith *et al.* (1983, 1984). Certainly some procedure should be used, because the presence of non-contributing variables in a "discriminant" analysis can greatly reduce its efficiency, although the superiority of any one procedure is not clear. Three of these papers are of particular note as they discuss the problems of homogeneity of covariance, which as pointed out earlier, is a concern often ignored, Beauchamp *et al.* (1980), Clausen and Harpoth (1983), and Chork and Govett (1985). A more nearly assumption-free approach named empirical discriminant analysis is based on kernel estimation, and by direct density estimation avoids the problems of multivariate normality and homogeneity of covariance. Examples or a discussion of this procedure may be found in Gustavsson (1980), Van den Boom *et al.* (1980), Gustavsson (1983), Rehder and Van den Boom (1983), and Armour-Brown and Olesen (1984). Some workers have used multiple discriminant procedures where more than two end-members are considered. In this method, new axes are derived that maximize the differences between groups and the data are usually plotted against the discriminant coordinates, sometimes referred to as canonical variates. However, this nomenclature can be confusing as canonical variates are also used to describe the new linear combinations arising from a canonical correlation study. R.E. Smith *et al.* (1983, 1984) have extensively used discriminant coordinates in their studies of pisolithic laterites of Western Australia to display their geochemical variability and how this relates to provenance. The probabilistic approach based on the computation of Mahalanobis distances has been used by Beauchamp *et al.* (1980), and R.E. Smith *et al.* (1983, 1984) to assist in classifying or allocating new individuals into a pre-established framework. The work of R.E. Smith *et al.* (1983, 1984) is particularly interesting as it touches on the problems of allocation procedure and because robust methods are used to compute the means and covariances essential to the method, thus leading to an improved statistical definition of background. Lastly, logistic regression as a discriminant tool has been little-used to date, probably due to the paucity of software to undertake the procedure and the complexity of the computations relative to linear discriminant analysis. However, Bonham-Carter and Chung (1983) described a comparative study where stepwise and multiple regression, and logistic regression, were used with geochemical data to estimate uranium resources.

RESOURCE APPRAISAL STUDIES

Resource appraisal can be differentiated from classical geochemical exploration in that it is used to make statements concerning areas rather than indi-

vidual sample sites. Resource appraisals attempt to quantify expected mineral resources in an area or region without being specific as to where those resources may be found. Within the field of resource assessment studies, there exists a technique referred to as the geochemical abundance model which relates crustal abundances to mass of element in a particular resource category (Garrett 1978, 1986; Harris 1984, 1988). A different approach is based on a log-binomial model where in a simulation a mass of crustal material of some average composition is subdivided into smaller and smaller blocks by a binary process, and with each subdivision the element is either concentrated into, or depleted from, the prior blocks subject to the constraint of mass conservation. The limit of this procedure is a lognormal distribution and the upper tail of this defines blocks of ore-grade (Harris 1984, 1988; Garrett 1986). The problem with this procedure, which is usually carried out on global, continental, or national scales, is with regard to its validity as smaller and smaller regions are studied. Garrett (1986) proposed a modeling procedure based on training areas of known mineral endowment as a potential solution to this problem.

Other resource appraisal procedures are based on subdividing the region to be studied into regular cells. Characteristic analysis, which has its roots in principal component analysis, was proposed as a technique for use in such studies (Botbol *et al.* 1978; and McCammon *et al.* 1983). Characteristic analysis involves coding the cells into -1, 0, +1 scale for the attributes, geochemical or otherwise, being used in the resource appraisal, the values indicate "response unfavourable", "not known", and "response favourable". To assist in this task, software has been published by Bridges *et al.* (1985). Regression approaches have also been used to forecast if a particular cell or area has a favourable mineral potential, e.g. Koch *et al.* (1981), and Bonham-Carter and Chung (1983). In fact once the departure from cell to area has been made it takes but little extension to proceed to geochemical drainage catchment basins, although this is getting closer to mineral exploration than resource appraisal (c.f. Aronof *et al.* 1986). However, this clearly demonstrates the continuum between regional resource appraisal and mineral exploration.

ARTIFICIAL INTELLIGENCE

To date, artificial intelligence, and in particular expert systems, have had little impact on exploration geochemistry. However, there have been some applications in mineral exploration that involve geochemical knowledge. The best known example is PROSPECTOR developed at Stanford Research Institute as part of a U.S. Geological Survey project (Hart *et al.* 1978, 1979; Campbell *et al.* 1982; and Maslyn 1986). PROSPECTOR involves deposit models and uses the presence or absence of particular trace element patterns associated with those de-

posit models as part of its decision-making process. The only example of a truly geochemical expert system for which some details have been published that the author is aware of is SERGE (Bonney *et al.* 1987). SERGE incorporates the knowledge obtained by Bureau de Recherches Géologiques et Minières staff members in interpreting geochemical mapping data from Brittany, France. Through a question-and-answer session, or direct interrogation of the data, SERGE classifies geochemical anomalies as to whether they are likely anthropogenic or geological, and if geological it attempts to classify the anomaly and assess its significance. It is likely that work is being undertaken on geochemical expert systems by others, but at this time little information is in the public domain.

COMPUTER MODELING

The availability of increased computing power and improved mathematical procedures have permitted geochemists to mathematically model many of the processes they hypothesize control the distribution of elements and minerals we observe today. The greatest amount of this work has concerned water-rock interactions, although other interesting studies have been made. In the field of water-rock and water-overburden reactions, the studies may be conveniently divided into two groups, firstly, those concerning mineral deposit formation and therefore what elements and minerals may be left by the path of mineralizing fluids; and secondly, those concerning the dispersal of elements in groundwaters from previously formed mineral deposits. All these studies are based on an important series of papers concerning thermodynamic modeling in the geological environment, including, Plummer *et al.* (1978), Parkhurst *et al.* (1980), Reed (1982), Parkhurst *et al.* (1982), Plummer *et al.* (1983), Flowers (1986), Perkins *et al.* (1986), and Deloule and Gaillard (1986) who consider the graphical presentation of the modeling results. Nordstrom *et al.* (1979) published the results of a major collaborative effort to assess the relative merits of the various aqueous systems modeling procedures, and it was from this that much of the development this decade stemmed. Studies involving ore-mineral deposition have been dominated by water-rock interaction modeling, these include work by Langmuir (1978), Sopuck and Lehto (1979), Runnells *et al.* (1980), and more recently with the shift of interest from U to Au and Ag, Cole and Drummond (1986) and Loucks (1986). In contrast, studies of ore-mineral dissolution and trace-element dispersion in groundwaters have been undertaken by Langmuir and Chatham (1980), Runnells and Lindberg (1981), Deering *et al.* (1983), Mann (1983), Rose *et al.* (1983), Snee (1983), and Lueck *et al.* (1978). The work concerning hydrogeochemical surveys has demonstrated very clearly the necessity of studying the trace-element composition of waters in the light of their total

chemistry, and in particular the role of the saturation index as computed for each sample site in such studies (Langmuir and Chatham 1980; Rose *et al.* 1983). A number of other studies have modeled various aspects of groundwater flow and chemistry of interest to the mineral explorationist, e.g. White (1979), Kimball (1981), Hull (1984), Montgomery *et al.* (1987), and Harris *et al.* (1987). All the previous work has concerned aqueous or ionic transport; two papers by Ruan, Hale, and Howarth (1985) and Ruan, Howarth, and Hale (1985) considered gaseous transport through overburden, and as such are similar in motivation to Snee's (1983) studies of ionic transport in overburden, both being concerned with the generation of geochemical anomalies at surface. Lastly, Donker (1987) has modeled various aspects of surface run-off and groundwater charge with respect to rainfall which has importance when modeling weathering processes and *in situ* geochemical anomaly development.

MICROCOMPUTERS AND GEOCHEMICAL DATA ANALYSIS

The availability of microcomputers and associated software has had a major impact on the way exploration geochemists work. Some software, e.g. the U.S. Geological Survey's GRASP and STATPAC data file management and data analysis programs, is available at nominal costs through the open file mechanism, whilst other software is in the commercial and consulting domains and has to be purchased. With reference to the U.S. Geological Survey, Dodd (1982) provided a catalog of available pre-1982 computer programs. Later packages such as the MIRA geochemical data analysis system (Hanley and Schruben, 1983) are also available. Specific microcomputer systems, some of which are available commercially, have been described by Lavin and Nichol (1981), Hoffman and Mitchell (1984), Koch (1986), and Lundholm *et al.* (1986). Several commercial geochemical data processing packages are available from companies in Europe and North America, but have not been described in the technical literature.

CONCLUSIONS

That the role of computers in exploration geochemistry is an important one is a fact as established by the wide diversity of published activity over the last decade. The published papers probably reflect the true diversity in all the fields discussed here, except probably artificial intelligence which is still in its infancy for exploration geochemistry. However, the number of research papers underestimates the volume of production work involving the use of computers, certainly the application of simpler statistical procedures that are used on a routine basis in many mineral industry and government surveys. This is partly due to the widespread availability of computing power in mini and microcomputers, but more

importantly to the availability of software packages and the acceptance of computer methods as routine tools. Much of the routine use of computing is with "canned" programs, bringing with it problems as well as benefits. Firstly, although it is easy to enter data into these software packages and obtain results, the user may not be fully aware of the assumptional rules of the methods being used, leading to disastrous interpretations. Secondly, the majority of the popular statistical packages that are in use were not written for geological users, e.g. BMDP, MiniTab, SAS, and SPSS on mainframe computers, and these and others such as Statgraphics and Systat available for microcomputers. Therefore, they are not always well adapted to geochemical practice and there is a lag between the development and publication of new procedures and their implementation in easy-to-use well-documented software packages. However, this is changing as more specifically geochemical software packages become available, although in general these are expensive in comparison with the widely used statistical packages due to their smaller market.

Geochemical data processing is mainly multivariate, and this situation will not change as improved analytical chemical procedures produce progressively more elemental analyses per sample at low cost. It is not surprising that over the last decade much of the published work has focussed on the recognition of patterns and outliers in multivariate datasets. Over the decade a new approach to multivariate data analysis and synthesis has become available through the use of image analysis systems. These have opened up a variety of new ways of viewing geochemical data and permit relationships with spatial features to be studied, whereas previously this was difficult and time consuming. The modeling work of today is multivariate in that many species and minerals may be considered simultaneously. The kind of approaches that these procedures make possible have had an enormous impact on hydrogeochemistry and the quality of data interpretation in that field. The modeling is both making it clear why we find the elements in abundance where we find them, and conversely allowing us to recognize what environments have been like in the past on the basis of the observed geochemical distributions. Modeling is playing an important role in changing exploration geochemistry from an observational science to a predictive one.

An important trend that has picked up momentum in the last decade has been the use of assumption- and distribution-free methods on one hand, and robust estimators on the other. Both of these approaches are resistant to statistical outliers, potentially the true geochemical anomalies being sought, but which can distort the procedures being used to detect them, resulting in poor definitions of background and therefore a reduced ability to recognize anomalies.

Very importantly there has been a complete change in attitude to computer-assisted interpretation over the past 20 years. Largely due to today's interactive and graphical computing environment, it is possible to carry out computer-assisted interpretations the way we would by hand if we ever had sufficient time. In an interpretation, geochemists partition data into groups on the basis of spatial or geochemical characteristics and provide each response group with a set of plausible geological and geochemical controlling processes, e.g. background lithological population or a mixture of lithological "end-members", secondary environmental modification, mineralization process, etc. The computer approach is to subdivide the data, preferably using interactive graphics, into subsets and then use whatever tool, graphical or statistical, is most appropriate to discover or confirm the processes associated with the response group. Thus many workers at the leading edge are developing what might be described as geochemist's interpretational tool-kits which combine a variety of data base (relational and/or geographic), graphical, statistical, and image analysis procedures into integrated systems which can be used in the intuitive ways of the geochemist. Interpretation can be likened to peeling an onion, one strips off data layer by layer, interpreting the layer(s) stripped at one stage using whatever tools are most appropriate; and then returning to the onion to strip off further layers, again using the most appropriate tool(s). This continues until the job is complete, and the necessary summaries, maps and graphics are prepared to convince an audience that the proposed interpretation is reasonable and complete.

THE NEXT DECADE

Crystal-ball gazing can be hazardous; in 1977 who would have realized that the computer power we have today would be so available on the geochemist's desk at such low prices. A remarkable spectrum of low cost hardware (computers, graphics devices, etc.) is now available and will become more powerful and cheaper in the future. What is missing is appropriate software embodying the best of the advances discovered by methodology developers in a way that makes them usable and, most importantly, helps the user employ them in a correct way. This will lead to a series of specialized workstation environments, some strong on computational power for modeling, others on graphics, and general purpose compromises, where geochemists can work with their data to achieve their particular objectives. Probably most of the techniques required to make competent interpretations already exist in data analysis, graphical methods, and image analysis. It is likely that important advances will be made in the sphere of algorithms for interpretation. Simply, how to approach a problem and knowing which tools are most likely to help solve the specific task at hand.

The next decade will see major advances in the use of geographic information systems (GIS), both at the institutional data base and individual project levels. Currently, the digital capture of thematic maps is a bottleneck, however, progress in raster scanning technology and the associated editing tasks will overcome this problem. This, coupled with reduced computer hardware and software costs will lead to a wide acceptance and use of GISs in exploration geochemistry and data integration studies. Advantages offered by this technology include a flexible electronic light-table approach which permits the evaluation of geochemical data and anomalies in the light of geological, geophysical, and other geoscience data, and the ability to produce maps which display only the features relevant to the particular problem under investigation.

In modeling exercises, increased computer power and improved methods will make it feasible to tackle ever more complex problems, and so realistically model the geochemical reality. A major benefit of these studies will be when practical rules can be developed for use in the field to recognize specific environments and their place in the overall scheme of element dispersion in the crust. Clearly, a part of this model is the processes and environments characteristic of element accumulation to form mineral deposits, and the later processes involved in their destruction and the dispersion of elements away from them.

All these activities involve knowledge. For instance, the design of geochemical exploration programs is largely heuristic and experience based, and much of this work is undertaken by mineral explorationists. There will be major attempts in the coming decade to try and organize the rules used by experienced geochemists in planning, managing, and interpreting geochemical surveys and other related activities into expert systems (Garrett and Leymarie, in press). If these are successful, they will have a major impact by improving the effectiveness of geochemical surveys in mineral exploration, which is surely our ultimate objective.

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47. Sample Representativity with Reference to Gold Exploration

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ABSTRACT

Attention is drawn to some of the particular considerations that have to be taken into account in designing and implementing an adequately reliable method for geochemical exploration for gold deposits. There has been a general tendency to adopt geochemical techniques developed successfully for the search for base-metal deposits to the search for gold deposits. Case history examples illustrate the very variable response of gold in different sample media with respect to gold deposits. Gold has a number of unique characteristics: a) very low natural abundance, b) frequent occurrence as native gold, c) very high specific gravity, and d) malleability. Collectively, these characteristics necessitate the adoption of specific techniques suited to gold exploration. The degree of representativity necessary frequently varies with each exploration program and each phase of a given exploration program. Adequate representativity requires the adoption of appropriate sampling, sample processing, analytical, and interpretational procedures. A prerequisite for necessary representativity requirements begins with the collection of an appropriately representative sample. This aspect is discussed from theoretical aspects, hypothetical models, and case history examples. An outline is given of the aspects to be taken into account in designing and implementing an optimum exploration program for gold deposits. In the absence of these considerations being taken into account, the overall reliability of geochemical exploration programs may be reduced with inevitable serious implications on the overall reliability of an exploration program.

INTRODUCTION

The object of this review is to consider the adequacy of geochemical exploration techniques applied to the search for gold deposits and to examine ways by which the overall reliability of these procedures may be increased. Successful exploration is dependent on the appropriate integration of a number of stages. Unfortunately, some of the more basic assumptions and stages are frequently overlooked. The importance of obtaining an adequately representative sam-

ple in the first instance is highlighted by Murphy (1982) as follows:

"No matter how sophisticated and precise the analytical instrumentation and treatment, statistical studies and modelling, or the financial analysis of mine potential, they will have little or no significance or profitable outcome, if the samples concerned are non-representative of the material or population being sampled."

Thus, in exploration, if less than adequate attention is given to obtaining an appropriate sample, no matter how much emphasis is focused on subsequent stages, the effectiveness of the overall program is at risk. Geochemical exploration comprises several distinct stages: sampling, sample preparation, analysis and interpretation, which can be likened to a multi-linked chain. If there is a weakness in any of these stages, in other words if one of these links breaks, then the overall effectiveness of the exploration effort may be seriously affected.

This presentation describes the history and background of geochemical exploration for gold, some case histories of geochemical exploration for gold, a consideration of the theory of sample representativity, and an examination of some hypothetical models. It then considers some of the problems that must be addressed to improve the effectiveness of exploration.

BACKGROUND TO GEOCHEMICAL EXPLORATION FOR GOLD

Recent economic factors have led to a marked concentration of exploration effort on the search for gold deposits. Prior to this shift in exploration interest, with certain notable exceptions, relatively little attention was focused on gold exploration, with correspondingly little interest shown in the development of exploration methods suited to the discovery of gold deposits.

Historically, geochemical exploration procedures for gold commonly involved the detection of anomalous zones of "pathfinder" elements such as arsenic, antimony, or mercury associated with gold mineralization. This approach was due in large part to the lack of the necessary sensitivity of methods for gold analyses. However, the weakness of this approach lay in the fact that not all gold occurrences have a pathfinder association and conversely not all anoma-

lous concentrations of pathfinder elements have gold associations. In areas where a high level of geological information is available, and gold deposits are of a type characterized by minerals and their constituent elements that can be used as pathfinders, then the use of pathfinders in geochemical exploration is advantageous. On the other hand, in areas where the base level of geological information on the character of expected mineral deposits in an area of interest is low, or there is a diversity in the character of gold deposits, associated minerals and element associations, there are obvious limitations to basing exploration on the determination of pathfinder elements and clear advantages in directly determining gold contents. On account of these limitations and the availability today of highly sensitive methods for the analysis of gold, much current geochemical exploration aimed at the discovery of gold deposits involves the direct analysis of gold.

Although the problems associated with obtaining a reliable estimate of the gold content of a sample have been recognized by those involved in the evaluation of gold deposits for a long time, the same cannot always be said of those concerned with the exploration for gold deposits.

Gold deposits occur in a wide range of geological environments, are characterized by different mineral associations and structural settings, and are related to a variety of formational processes. Subsequently, these deposits have been subjected to a range of weathering and dispersion processes resulting in a wide variety of responses to mineralization in different sample media. Most significantly, as far as geochemical exploration is concerned, the concentration levels of interest, together with the grain size of gold particles, vary from deposit to deposit.

In the surface or secondary environment, gold may occur as tellurides, as inclusions in sulphides, associated with iron or manganese oxides, clay minerals and organic matter, or as particulate gold. It is in the latter case that the greatest potential for representativity problems exists. These problems arise from the fact that, in the particulate form, gold occurs as the major component in a very minor constituent. Natural concentrations in the ppb range are frequently of significance, which is three to four orders of magnitude lower than that of base metals. These concentrations can be represented by very few particles of gold. Significant gold contents in samples are frequently caused by very few particles, which creates a serious problem of collecting a representative sample in the first instance and then subsequently preparing a representative sample for analysis. Common practice is for a 10 to 30 g sample to be analyzed for gold and the data to be evaluated on the basis of the absolute gold concentration. The question that arises is how adequate is this practice? In the absence of a representative sample being taken for analysis, the reliability and confidence that can be attached to the results are limited. A consid-

erable amount of highly relevant information on sample representativity is available in the literature, but to a large extent this critical information appears to have been disregarded in the design and implementation of exploration programs aimed at the discovery of gold deposits.

CASE HISTORY EXAMPLES

Examination of the distribution of gold in a variety of sample media indicates some very variable relationships that have considerable bearing on the application of geochemical exploration techniques to gold exploration. With regard to Canada, and more specifically the Canadian Shield, many areas presently attracting considerable exploration attention are characterized by a cover of deep glacial overburden. Geochemical exploration in these areas is aimed at the collection of lodgment till on the basis that this material is of more local derivation and most likely carries a reflection of any mineralization in the up-ice direction. A significant proportion of this exploration is based on reverse circulation drilling; however, a sample collected using this system is unrepresentative of the parent till, because the majority of the fine-grained material is lost at the sample collection stage (Averill and Thomson 1981; Nichol and Shelp 1985). A bulk sample of the till, normally 5 to 10 kg, is then screened, frequently to minus 10 mesh (<2 mm), and passed over a gravity table. The table concentrate is then treated with heavy liquids and the heavy liquid fraction separated into a non-magnetic and a magnetic fraction. The non-magnetic fraction is then analyzed. Conventionally, concentrations of gold greater than 1000 ppb to 3000 ppb are considered anomalous, whereas lower concentrations are regarded as background. The objective is to detect anomalous concentrations of gold that reflect mineralization in the area. This approach has contributed significantly to gold exploration in the Canadian Shield in recent years. For example, the Aquarius Deposit, east of Timmins, was discovered as a result of the detection of anomalous gold concentrations in the till over and down-ice from the deposit (Gray 1983) (Figure 47.1). This information allowed the identification of drilling targets which led to the discovery of the Aquarius Deposit. In contrast, results from a similar till sampling program in the area of the McBean Mine, east of Kirkland Lake, failed to reveal any anomalous response in gold content in the heavy mineral concentrate (Figure 47.2). By contrast, markedly anomalous gold contents in till samples are present a few kilometres to the west, associated with the Biroco Deposit. Whereas the McBean Deposit represents a significant deposit, the present evidence is that the Biroco Deposit is subeconomic. The reason for lack of any response in till down-ice from the McBean Mine is not fully understood. Lodgment till in the McBean open pit apparently down-ice from the deposit is not anomalous, indicating that

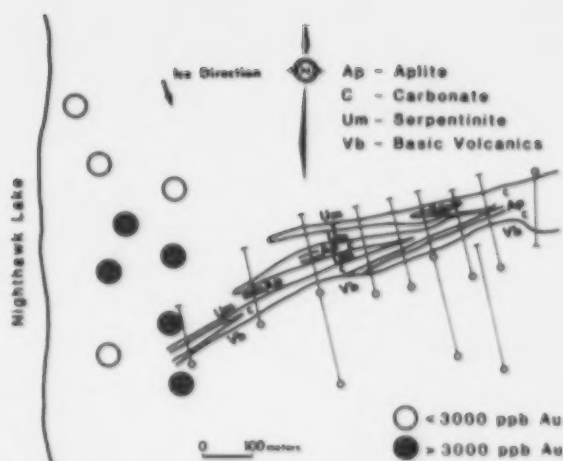


Figure 47.1. Distribution of gold in heavy mineral concentrates of till associated with Aquarius deposit, Ontario (after Gray 1983).

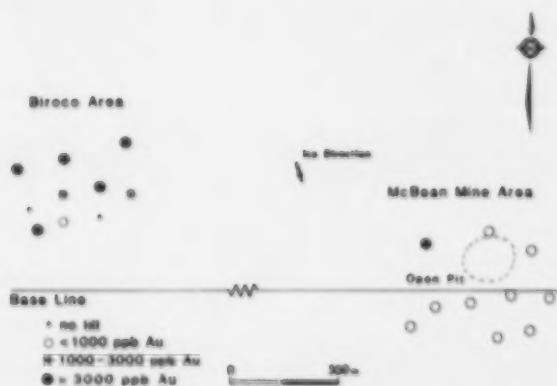


Figure 47.2. Distribution of gold in heavy mineral concentrates of till associated with the McBean Mine and the Biroco deposit (with permission of Inco Limited).

the glacial event that gave rise to the deposition of the lodgment till down-ice from the deposit did not erode material from the deposit, and thus does not contain any reflection of the deposit.

Similarly, an orientation survey carried out in the area of a number of gold deposits in the Beardmore-Geraldton area of northwestern Ontario showed markedly different responses in different sample media amongst three deposits (Closs and Sado 1979). The gold dispersion in the minus 177 μm fraction of B horizon soil (Figure 47.3) and the minus 250 plus 63 μm heavy mineral fraction associated with the Northern Empire Gold Occurrence, as determined by the analysis of 10 g samples, displays erratic responses related to mineralization. The distinction of the dispersion related to

the mineralization is complicated by an additional gold occurrence up-ice. In contrast, at the Archie Lake area, weakly anomalous gold concentrations occur in the B horizon soils, whereas at Knox Lake, anomalous gold concentrations occur in the minus 177 μm fraction of soil, the minus 63 μm fraction of till, and the minus 250 plus 63 μm heavy mineral fraction of till. The occurrence of anomalous gold in the minus 177 μm fraction of soil and the minus 250 plus 63 μm fraction of till and its absence in the 63 μm fraction of till associated with the Northern Empire Gold Occurrence is attributed to the gold occurring as visible gold in the primary mineralization (Benedict and Titcombe 1948). The very restricted nature of the anomalous dispersion pattern in soils and the lack of response in till associated with the Archie Lake Occurrence are attributed to the apparent limited suboutcrop of the mineralization. The occurrence of anomalous responses in the minus 177 μm fraction of B horizon soil, the minus 250 plus 63 μm heavy mineral fraction, and the minus 63 μm fraction of till (Figure 47.4) associated with the Knox Lake Deposit is attributed to the occurrence of gold in the 2 to 20 μm size range. A characteristic of the dispersion trains associated with all these deposits is their spotty nature. In part, this may be attributed to variation in sample type; however, this feature may also be related to the sample size being too small to provide a representative analysis.

Now considering the distribution of gold in stream sediments, in an extremely thought-provoking paper, Harris (1982) described the distribution of highly variable gold results from an area in southern British Columbia. In this study, 5 g samples of the minus 177 μm (80 mesh) fraction of stream sediment were analyzed for gold. The analytical procedure had a 10 ppb detection limit and 20 ppb was established as the threshold value. Difficulty was experienced in reproducing the initial analyses of reconnaissance samples by re-analysis and in order to examine the matter further, 95 samples were analyzed in triplicate (Figure 47.5). Of these 95 samples, 70 displayed background concentrations in all three analyses. In contrast, six samples, which on the initial analyses showed anomalous gold contents, displayed anomalous gold contents in one of the subsequent analyses confirming the original anomalous value. In the case of six other samples, which initially indicated anomalous gold contents, all subsequent analyses revealed background gold contents. Thus, if follow-up operations had been undertaken on the basis of the initial analysis, it would have amounted to wasted effort as the initial anomalous values were discounted on replicate analyses. In a fourth group of seven samples that on first analysis indicated background concentrations of gold, anomalous contents were revealed in one or other or both subsequent analyses. Thus, if interpretation had been based on the initial analysis, no follow-up would have been undertaken and possible minerali-

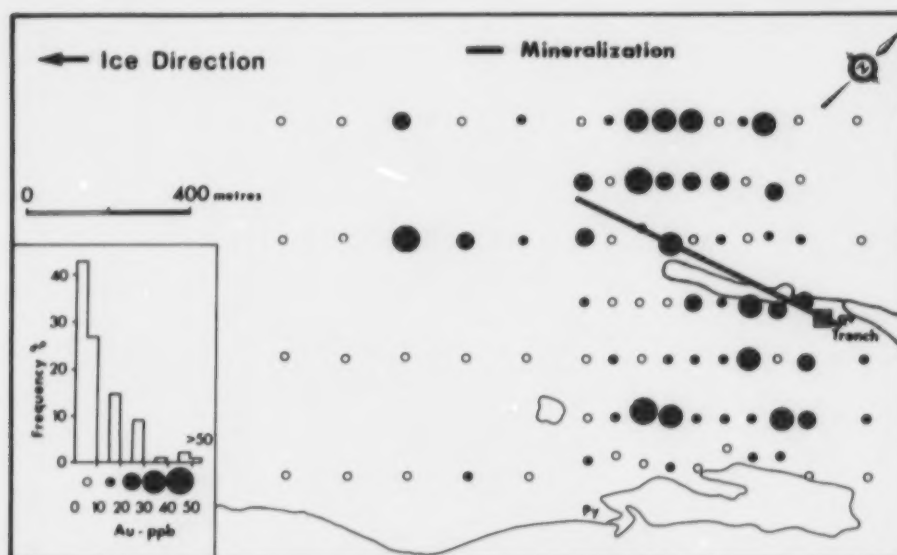


Figure 47.3. Gold distribution in B horizon soil from the Northern Empire area, near Beardmore-Geraldton, Ontario (from Closs and Sado 1979).

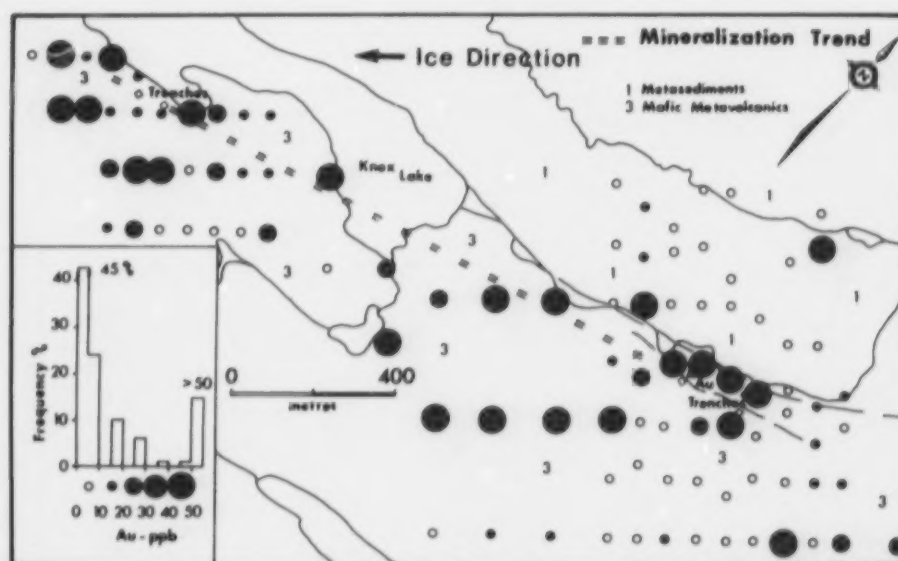


Figure 47.4. Gold distribution in the minus 63 μ m fraction of till samples from the Knox Lake area near Beardmore-Geraldton, Ontario (from Closs and Sado 1979).

zation might have been overlooked, whereas subsequent analyses indicated anomalous gold contents that warranted follow-up.

In a supplementary investigation by Harris (1982), replicate analyses of three samples displayed relative standard deviations of from 208 to 412 percent at the 95 percent confidence level. In addition, significant variations in replicate analyses and rela-

tive standard deviations were noted amongst samples collected within a short distance of one another. This situation draws attention to the distinct possibility of overlooking anomalous locations and has serious implications in terms of exploration reliability.

To summarize, from the examples discussed, it can be concluded that the response to mineralization varies according to sample type, size fraction, min-

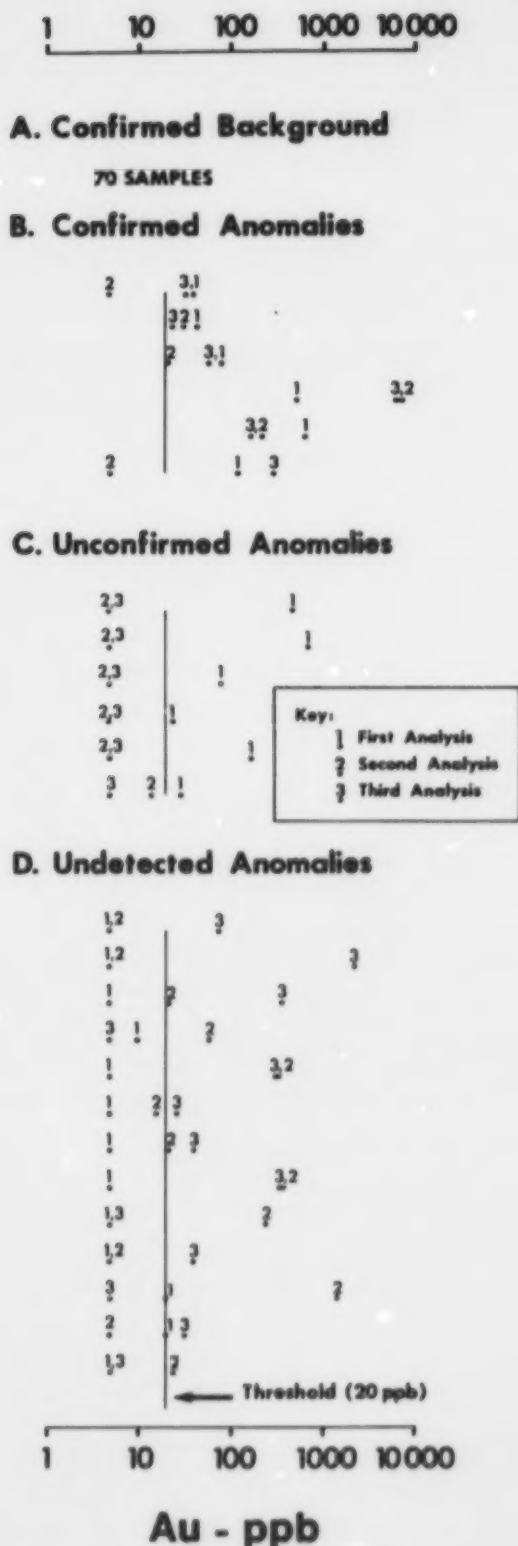


Figure 47.5. Replicate gold analyses of stream sediments from the Rossland area, British Columbia (adapted from Harris 1982).

eral fraction analyzed, replicate analysis, and, most importantly, the actual areal extent of the anomalous response. Collectively, these features draw attention to the potential dangers of basing interpretation of geochemical data strictly on the indicated gold content of samples. Whilst geochemical exploration methods have undoubtedly met with some success in aiding the discovery of significant gold deposits, the questions that arise are: firstly, have significant deposits been overlooked, and secondly, can we improve the reliability of the methods employed to increase the chances of exploration success?

THEORETICAL CONSIDERATIONS

It is appropriate to examine some theoretical considerations of sample representivity to see whether the variable response can be due in part to non-representivity of the samples collected.

The overall variability can be quantified by the variance in an element's content within a set of data and is related to two main sources: a) the natural or regional variability in the element content over the area; and b) variability introduced by sampling, sample processing and analyses. The variability or variance S^2 in a data set can thus be expressed in terms of the sum of a number of individual variances as follows:

$$S^2 = S^2_{ntr} + S^2_{spl} + S^2_{prc} + S^2_{anal}$$

where:

S^2 - total variance

S^2_{ntr} - natural variance

S^2_{spl} - sampling variance

S^2_{prc} - sample processing variance

S^2_{anal} - analytical variance

The variance can be considered a measure of the representivity. The total variance in a set of data is the sum of the natural variance plus the sampling variance plus the sample processing and the analytical variance. In exploration, it is the natural variance (or the variability between sample sites) that is of interest. Sampling, sample processing, and analytical variance can be considered as introduced variance that needs to be controlled within acceptable limits.

In geochemical exploration, the objective is to distinguish anomalous concentrations related to mineralization from background concentrations. The magnitude of the difference between anomalous and background concentrations varies from area to area and so does the necessary representivity of the samples. In situations where there is no clear distinction between anomalous and background populations in a data set, one of the conventions used in geochemical exploration is to regard the mean con-

centration plus two standard deviations as the threshold value, i.e. the concentration that separates anomalous contents from background contents. By way of illustration, in an idealized frequency distribution curve, there may be a relatively small range in concentration for population A (Figure 47.6), i.e. the difference between threshold concentration (T_A) and the mean background ($\bar{x}$) is relatively small. Thus, in this situation, a relatively high degree of representativity is required to confidently recognize threshold from background concentrations. In contrast, in a situation where there is a relatively large difference between threshold (T_B) and mean background, as in population B (Figure 47.6), a lower degree of representativity would be adequate to identify anomalous concentrations. In these examples, it is assumed the anomalous population constitutes a relatively small proportion of the entire population, as might be the case in reconnaissance level exploration. However, in detailed exploration, where a much larger proportion of the samples would be expected to contain anomalous concentrations, the same underlying considerations apply in terms of representativity requirements. The essential point to be recognized is that the degree of representativity required varies between programs and within exploration stages of a program. The distinction of anomalous concentrations, or even degree of anomalous concentrations, must not be obscured from background populations by poor representativity.

Consider now two situations and assume that a 10 g sample is taken for analysis on the basis that a 10 g sample weight is frequently used in exploration. In the first case, two 100 g samples, A and B (Figure 47.7) contain the same gold content. In sample A, the gold is contained in a single grain, a nugget. If 10 subsamples, each of 10 g, are taken from this

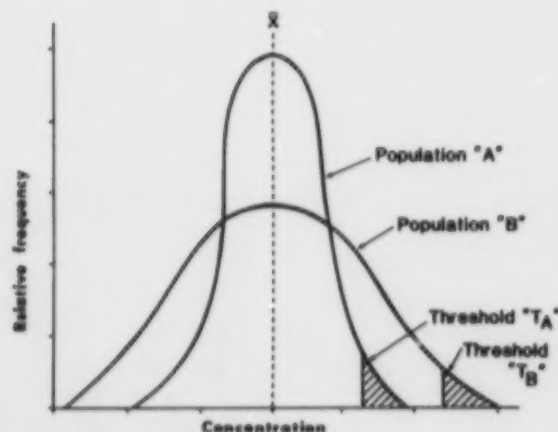


Figure 47.6. Data distributions with varying contrast between threshold and mean background.

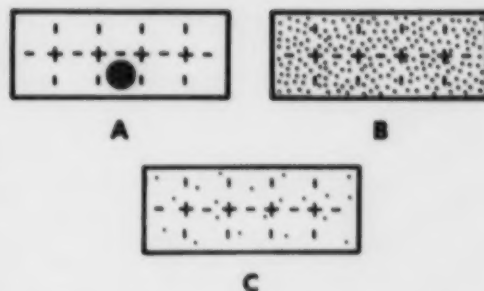


Figure 47.7. Variation of representativity of sample for analysis according to particle size (A and B) and concentration with constant size gold particles (B and C) (in part from Harris 1982).

100 g sample, then nine subsamples will contain no gold and one sample will contain ten times the true value. In sample B, which contains the same total gold content but in very fine grain sized gold particles, each of the 10 g subsamples will give a value that very closely approximates the true value. From this example, it is clear that for samples of equal gold content, the coarser the gold, the larger the sample that must be analyzed to obtain a representative value. A variation on this theme, demonstrated by Harris (1982), considers two samples that have gold particles of the same size, but with different concentrations. In the sample with low gold content, C, (Figure 47.7), 10 g subsamples may have one, two, three or even no grains of gold in them. In other words, these subsamples will have highly variable gold contents and individual subsamples will have poor representativity. In the other case (sample B, Figure 47.7), where the gold content is much higher, any 10 g subsample will yield a reproducible value. From this, it can be seen that for samples containing gold particles which are the same size, the lower the gold content, the larger the sample required for a given level of representativity.

The classic work of Gy (1954) on sample representativity, together with later work by Clifton *et al.* (1969), is particularly pertinent to providing guidelines on sample representativity in gold exploration. Collectively, this information provides an excellent foundation for the appropriate collection, preparation, and analyses of samples for gold exploration. Gy (1954) published a formula for establishing the representativity of ore sampling, which has subsequently been described by Outley (1966, 1983). The same formula is directly applicable to geochemical exploration:

$$S^2 = \frac{Cd^3}{M}$$

where:

S^2 = the relative variance of a data set

- S = the relative standard deviation (Note: standard deviation must be expressed in relative terms in Gy's formula)
- C = a sampling constant for the particular material to be sampled which is related to parameters characteristic of the sample
- d = aperture of the sieve passing 95% of the sample (cm) hereinafter referred to as "maximum significant grain size"
- M = sample weight (g)

The formula can be used to determine:

1. The representativity or variability to be expected using a particular sample weight and type of sample (equation shown above).
2. The weight of sample required to achieve a particular variance.

$$M = \frac{Cd^3}{S^2}$$

3. The necessary mechanical size for a given sample weight to achieve required variance.

$$d = \sqrt[3]{\frac{MS^2}{C}}$$

The use of the formula assumes random sampling, implies no bias in the sample processing and, furthermore, takes no account of any analytical errors. A method for gold analysis that involves a 10 g sample is considered. This method assumes that the 95th percentile of gold grain sizes are at various sizes in the range 250 to 1 μm (gold contents), and are at various concentrations between 1000 and 1 ppb. If Gy's equations are used, the precision at the 95 percent confidence level (represented by the range: $X \pm$ standard deviation) shows some very marked variations (Table 47.1), based on calculations by D. Ottley (Independent, personal communication, 1987). For example, at the 1000 ppb level and 63 μm the maximum significant grain size, precision is ± 28 percent which would be acceptable in most exploration programs concerned with determining gold at this concentration level. In contrast, at the 16 ppb level and for gold particles of the same size (63 μm), the variation is ± 218 percent which means that 95 percent of replicate analyses would lie within 16 ppb ± 218 percent. These limits would have a questionable acceptability in most geochemical exploration programs. It is clear that the precision or representativity of gold contents improves with decreasing particle size for a given concentration. Similarly, the representativity of gold analyses deteriorates with decreasing gold content for a constant particle size.

As discussed previously, in geochemical exploration it is necessary to achieve a particular level of representativity to distinguish, with confidence, be-

tween anomalous and background concentration levels. If it is assumed that a precision of ± 50 percent is required, then, using Gy's formula, it is possible to determine the weight of sample necessary to give this precision for a range of grain size and gold concentrations. The minimum required sample weights for samples with a range of gold grain sizes and bulk compositions are shown in Table 47.2 (D. Ottley, Independent, personal communication, 1987). In this case, the very marked increase in sample weight necessary to provide ± 50 percent precision with increasing gold particle size at constant concentrations and/or decreasing gold content for a constant particle size is very clear.

A comparable approach was described by Clifton *et al.* (1969) who made the assumption that all particles of gold in a sample are of the same size. This assumption is very rarely true in nature, but is acceptable for the present purpose. Clifton *et al.* (1969) further assumed that the gold particles are randomly distributed, the particles represent less than 0.1 percent of all particles, samples contain more than 1000 particles in total, and analytical errors are neglected.

Clifton *et al.* (1969) showed and quantified how analytical precision deteriorates as the number of particles in a sample analyzed decreases (Figure 47.8). Furthermore, in order to achieve a precision of ± 50 percent at the 95 percent confidence level, it is shown that it is necessary to take a sample that contains at least 20 particles of gold. These authors then showed the relationship between weight of sample containing 20 particles of gold, particle size and gold concentration (Figure 47.9). For example, in a sample containing 1 ppm gold where the gold is contained in discs with diameter five times the thickness (250 μm in diameter and 50 μm thick), a sample of some 1 kg would contain the necessary 20 particles. In a sample containing the same 1 ppm Au content, but as discs of 32 μm diameter, 20 particles would be contained in a sample weight of approximately 1 g. The weight of sample containing 20 particles of gold as discs with diameter five times the thickness, for various combinations of concentration and particle size is shown in Table 47.3. In essence, the results show the same trend as those obtained using the formula of Gy (1954).

As was shown with Gy's formula, it is clear how the necessary size of sample to be collected dramatically increases with increasing size of particle for a given gold concentration and similarly increases with decreasing concentration for a constant particle size. It should be realized that the entire sample that needs to be collected must be analyzed or alternatively some procedure adopted to produce a representative subsample. If a sample of 10 g is being analyzed, which is common practice, then the area under the stepped line (Table 47.3), is the area of adequate representativity; any combination of gold particle size and concentration over the line is unsat-

TABLE 47.1. PRECISION, AT THE 95% CONFIDENCE LEVEL, OF GOLD ANALYSES OF A 10 G SAMPLE ACCORDING TO PARTICLE SIZE AND CONCENTRATION DETERMINED BY THE METHOD OF GY (1954).

GOLD GRAIN SIZE (μm)	GOLD CONCENTRATION (ppb)					
	1000	250	64	16	4	1
250	220	436	862	1723	3446	6892
125	88	154	314	608	1217	2433
63	28	55	109	218	436	872
32	10	20	39	79	158	316
16	3.5	7	14	28	56	112
8	1.2	2.5	5	10	20	39
4	0.4	0.9	1.7	3.5	7	14

Precision is in percent.

TABLE 47.2. SAMPLE WEIGHTS NECESSARY TO ACHIEVE $\pm 50\%$ PRECISION, AT THE 95% CONFIDENCE LIMITS, ACCORDING TO PARTICLE SIZE AND CONCENTRATION DETERMINED BY THE METHOD BY GY (1954).

GOLD GRAIN SIZE (μm)	GOLD CONCENTRATION (ppb)					
	1000	250	64	16	4	1
250	190	760	3.0 kg	12 kg	48 kg	190 kg
125	24	95	371	1.5 kg	5.9 kg	24 kg
63	3	12	48	190	760	3.0 kg
32	0.4	1.6	6.2	25	100	400
16	50 mg	0.2	0.8	3.1	13	50
8	6 mg	20 mg	0.1	0.4	1.6	6.2
4	0.8 mg	3 mg	12 mg	49 mg	0.2	0.8

Sample weights are in grams except where shown.

TABLE 47.3. WEIGHT OF SAMPLE CONTAINING TWENTY PARTICLES OF GOLD (DIAMETER IS FIVE TIMES THICKNESS) ACCORDING TO CONCENTRATIONS OF GOLD AND SIZE OF GOLD PARTICLES DETERMINED BY THE METHOD OF CLIFTON ET AL. (1969).

GOLD GRAIN SIZE (μm)	GOLD CONCENTRATION (ppb)					
	1000	250	64	16	4	1
250	930	3.7 kg	15 kg	58 kg	230 kg	930 kg
125	120	470	1.8 kg	7.3 kg	29 kg	120 kg
63	15	60	230	930	3.7 kg	15 kg
32	2	8	31	120	490	2 kg
16	240 kg	1	4	15	64	240
8	31 mg	120 mg	480 mg	2	8	31
4	4 mg	15 mg	60 mg	240 mg	1	4

Sample weights are in grams except where shown.

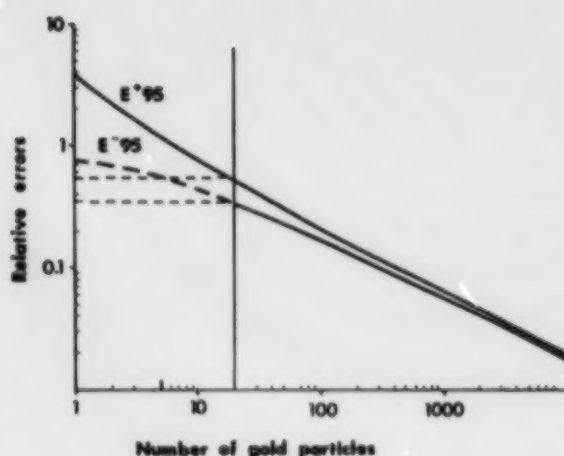
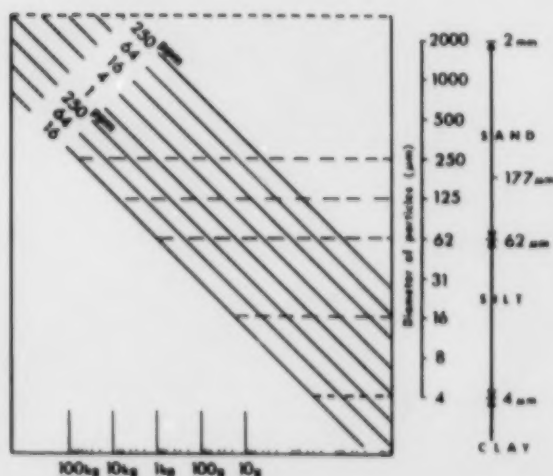


Figure 47.8. Variation of precision with number of gold particles contained in sample (from Clifton et al. 1969).



Weight of sample containing 20 particles of gold

Figure 47.9. Variation of weight of sample containing 20 particles of gold according to particle size and gold concentration. Gold particles are flakes in which the diameter is five times the thickness (modified from Clifton et al. 1969).

isfactory. For example, analysis of a 10 g sample is inadequate for samples containing 63 μm diameter discs of gold for concentrations in the range 1 to 1000 ppb, but adequate for samples containing 4 μm diameter gold discs for all the above concentrations. However, the suitability of an analysis of a 10 g sample with gold particles in the range 8 to 32 μm varies within the concentration range 1 to 1000 ppb.

On the basis of the size of sample containing 20 particles of gold, it is possible to determine the num-

ber of gold particles expected in a 10 g sample, depending on gold particle size and gold content. Where this number falls below 20, then there are too few gold particles to give the ± 50 percent precision at 95 percent confidence level. The combination of conditions of particle size and gold content for which the number of particles exceeds 20 (Table 47.4) and, therefore, meets the ± 50 percent precision of representativity requirements at the 95 percent confidence limits, is of course identical to the area of adequacy indicated on the basis of a 10 g sample (Table 47.3).

The question that arises is what precision or representativity will be introduced by the collection and analysis of an inadequately sized sample. The relationship between the range of analyses or representativity and the number of particles expected in a sample analyzed is illustrated by Clifton et al. (1969) (Figure 47.10). If, on the basis of the gold grain particle size, gold concentration and the sample weight collected and analyzed, the particle expectancy in the sample analyzed is approximately one gold particle (e.g. 64 ppb Au and 63 μm diameter particles as indicated in Table 47.4), then 37 percent of replicate analyses will contain no particles. Thirty seven percent will contain one particle and indicate the true value, 19 percent will contain two particles and give twice the true value, whilst the remaining 7 percent will contain more than two particles and indicate some integral multiple of the true value greater than two. If, on the other hand, on the basis of gold concentration and particle size, the particle expectancy in the sample analyzed is 0.1 (e.g. 64 ppb and 125 μm Au) then 90 percent of the samples will contain no gold and 10 percent will contain some combination of 10, 20, or 30, etc. times the true value.

The decrease in precision or representativity with decreasing number of particles expected in the sample analyzed is illustrated in Figure 47.11. It can be seen that, with a particle expectancy of 20, a ± 50 percent precision at the 95 percent confidence level is achieved; however, as the particle expectancy decreases, the precision or representativity of the analysis deteriorates dramatically.

If these observations are related to exploration, the relevance of them can be demonstrated by two hypothetical examples. In these two instances, overburden associated with significant gold mineralization has uniformly anomalous dispersion containing 64 ppb Au (assuming no downslope or down-ice dilution). In case "A", gold occurs as 63 μm discs, whereas in case "B" gold occurs as 125 μm discs. Assuming a 10 g sample is analyzed, these situations are equivalent to particle expectancies of 0.9 and 0.1, respectively (Table 47.4). The resulting distribution of gold contents is illustrated in Figure 47.12. It can readily be seen that the "noise" in the data, reflecting poorer representativity, increases dramatically as the size of gold particles increases and the

TABLE 47.4. NUMBER OF GOLD GRAINS EXPECTED IN A 10 g SAMPLE TAKEN FOR ANALYSIS ACCORDING TO CONCENTRATION OF GOLD AND SIZE OF GOLD PARTICLES DETERMINED BY THE METHOD OF CLIFTON *ET AL.* (1969).

GOLD GRAIN SIZE (μm)	GOLD CONCENTRATION (ppb)					
	1000	250	64	16	4	1
250	0.2	0.05	0.01	0.003	0.0009	0.0002
125	1.7	0.4	0.1	0.03	0.007	0.002
63	13	3	0.9	0.2	0.06	0.01
32	100	25	7	2	0.4	0.1
16	800	200	50	13	3	0.8
8	6700	1640	400	100	25	7
4	53000	13000	3300	800	200	50

Sample weights are in grams except where shown.

particle expectancy decreases. The fundamental question that arises is how confident can we be that either or both of these deposits will be recognized?

The previous discussion is based on the assumption that all gold particles are of the same size. In nature, gold particles generally cover a range of sizes and the magnitude of the range varies amongst deposits. In a case where a sample taken for analysis contains 20 particles of gold of variable size, the use of the average size of particles in determining the weight of sample to be analyzed to give ± 50 percent precision will be incorrect and low. In fact, the effective grain size, by definition the grain size that can be used to determine the weight of sample to be analyzed to give ± 50 percent precision, is greater than the average grain size.

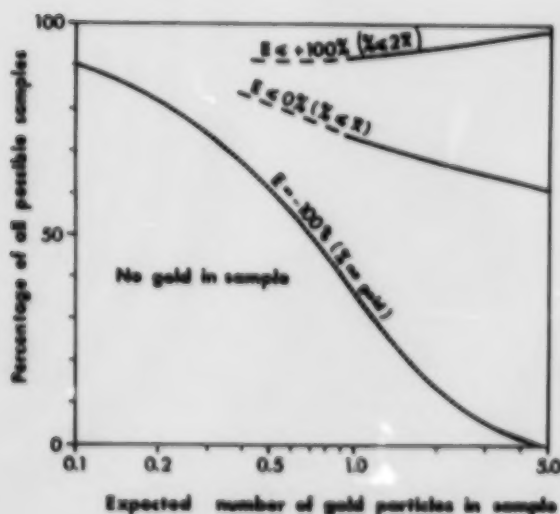


Figure 47.10. Variation of range of values according to number of particles expected in a sample taken for analysis (from Clifton *et al.* 1969).

Effective grain size may be determined on the basis of: a) the measured gold particle size distribution; b) the variance of replicate analyses of unsized splits of a sample; and c) the maximum size of gold particles that make a significant contribution to the gold content of a sample (Clifton *et al.* 1969).



Figure 47.11. Histograms of range of values according to number of gold particles expected in sample taken for analysis.

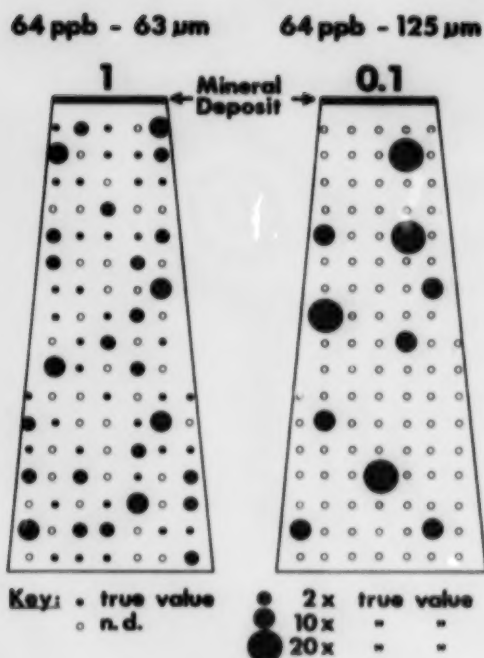


Figure 47.12. Distribution of gold according to number of particles expected in a 10 g sample taken for analysis.

Prigogine (1961) and Gy (1967) have shown that the effective grain size, based on grain size distribution of the gold particles, can be calculated by the equation:

$$d_e = \sqrt[3]{\sum_j \frac{M_j}{M} d_j^3}$$

where:

- d_e is the effective grain size, or diameter
- M_j is the mass of gold in size grade j
- d_j is the midpoint diameter of size grade j
- M is the total mass of gold.

In a number of cases, exploration practice is to analyze the minus 63 μm fraction of a natural sample on the assumption that a 10 g sample will be adequately representative because of the fine-grain size of the sample. The validity of this assumption will now be examined. The effective grain size diameter (μm) has been calculated for the hypothetical samples in which the gold is variously distributed in different size ranges within the minus 63 μm fraction (Table 47.5). In the case of sample 1, it has been assumed that all gold particles are 63 μm in diameter to portray a worst case situation. Subsequently, the weight of sample containing 20 particles of gold according to the different effective diameters

has been determined for gold concentrations of 1000, 100, and 10 ppb, respectively (Table 47.6). This shows that for a concentration of 1000 ppb, only when the particles are 63 μm in diameter is the sample weight containing 20 particles more than 10 g; however, at concentrations of 100 ppb and effective particle diameters greater than approximately 25 μm , the appropriate sample weight is greater than 10 g. At 10 ppb, the appropriate sample weight exceeds 10 g at effective particle diameters of 10 μm .

The implications of the above data are that when the minus 63 μm fraction of natural samples is being analyzed in situations where 100 ppb gold is of interest, then the effective grain size of gold has to be reduced to some 25 μm . Similarly, if 10 ppb is considered to be significant, the effective particle size has to be reduced to some 15 μm .

Alternatively, effective grain size may be estimated on the basis of replicate analyses of unsized splits. On the basis of replicate analyses of say 50, 10 g subsamples, it is possible to determine the mean ($\bar{X}$), the standard deviation (s), and the relative standard deviation (s_r). If the relative standard deviation is considered, it is possible to determine the number of gold particles in the sample weight analyzed (in this case 10 g) from Figure 47.7 and thus, the weight of sample containing 20 particles.

An example of determining the necessary sample weight to be analyzed to provide ± 50 percent precision at the 95 percent confidence level is illustrated with reference to replicate analyses of: 1) a glacial till sample associated with the Owl Creek Gold Deposit near Timmins, Ontario; and 2) a drainage sediment from the Carlin area of Nevada. Replicate analyses of 25 g subsamples of each sample revealed markedly skewed distributions (Figure 47.13). On the basis of the mean contents and relative standard deviations, the effective grain sizes and sample weights required to give ± 50 percent precision were determined. These indicate necessary sample weights of 1010 and 760 g for the Owl Creek and Nevada samples, respectively (Table 47.7). The frequency distributions of replicate analyses of both samples show the existence of a few erratically high values greater than 1000 ppb suggesting the presence of erratically distributed nuggets.

If information on the size distribution is unknown and replicate analyses of splits are not available, the appropriate sample size can be determined on the basis of considering the effective size as the size equal to the maximum significant size, a size below which 95 percent of the total gold is contained. This approach assumes that gold particles are all the same size and equivalent to the 95th percentile size. This procedure provides an additional safety margin relative to the procedures involving consideration of the size distribution of the gold and the variability of replicate analyses. A comparison of the results of these approaches on a magnetite-rich beach sand from Oregon with a content of 380 ppb

TABLE 47.5. EFFECTIVE DIAMETER OF GOLD PARTICLES OF VARYING SIZE RANGES IN THE MINUS 63 μm FRACTION OF TEN SAMPLES DETERMINED BY THE METHOD OF CLIFTON *ET AL.* (1969).

SAMPLE	SIZE FRACTION (μm)					EFFECTIVE DIAMETER (μm)
	64-32	32-16	16-8	8-4	4-2	
1	100*	-	-	-	-	63
2	50	20	15	10	5	38
3	20	20	20	20	20	29
4	5	50	25	15	5	23
5	5	20	50	20	5	21
6	5	15	25	50	5	20
7	5	10	15	20	50	19
8	-	5	10	15	70	10
9	-	-	5	20	75	5
10	-	-	-	-	100	3

* In sample 1 all grains are assumed to be 63 μm in diameter (worst case example).

TABLE 47.6. SAMPLE WEIGHTS (g) NECESSARY TO ACHIEVE $\pm 50\%$ PRECISION, AT THE 95% CONFIDENCE LIMITS, ACCORDING TO EFFECTIVE DIAMETER AND CONCENTRATION, DETERMINED BY THE METHOD OF CLIFTON *ET AL.* (1969).

SAMPLE	EFFECTIVE* DIAMETER (μm)	GOLD CONCENTRATION (ppb)		
		1000	100	10
1	63	15	150	1.5 kg
2	38	3.3	33	330
3	29	1.5	15	150
4	23	730 mg	7.3	73
5	21	550 mg	5.5	55
6	20	480 mg	4.8	48
7	19	410 mg	4.1	41
8	10	60 mg	600 mg	6.0
9	5	7.5 mg	75 mg	750 mg
10	3	1.6 mg	16 mg	160 mg

* Gold grains represented as discs with disc diameter equal to 5 times height.

Sample weights in grams except where shown.

TABLE 47.7. SAMPLE WEIGHT NECESSARY TO ACHIEVE $\pm 50\%$ PRECISION, AT THE 95% CONFIDENCE LIMITS, BASED ON REPLICATE ANALYSES OF 25 g SUBSAMPLES.

SAMPLE	NUMBER OF SUB-SAMPLES	MEAN (ppb)	COEFFICIENT OF VARIATION	NO. PARTICLES PER 25 g SAMPLE	REQUIRED SAMPLE WEIGHT (g)
Nevada	176	197	1.42	0.50	1010
Owl Creek	256	235	1.23	0.64	758

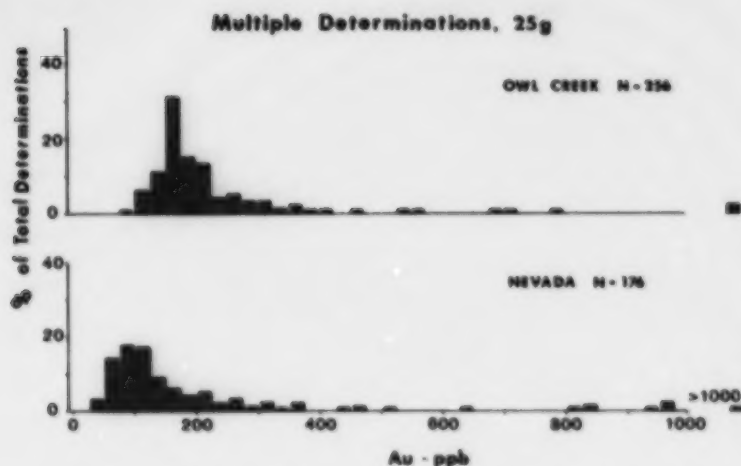


Figure 47.13. Frequency distribution of replicate analysis of 25 g subsamples from two bulk samples.

Au shows a variation in the effective particle size from 170 to 270 μm equivalent to necessary sample weights varying from 300 to 1500 g (Clifton *et al.* 1969). This difference in necessary sample weights reflects variations in assumptions between the different approaches.

DISCUSSION AND CONCLUSIONS

In summary, it is apparent from a consideration of case history data and theoretical aspects that the reliability of some of the geochemical exploration activities being carried out is relatively low. The result is that only limited confidence can be placed on the results. Whilst fully acknowledging the important role that geochemical techniques have played in the discovery of some deposits, the inevitable concern that arises is how many deposits have been overlooked because of the shortcomings of the techniques adopted?

The description of theoretical aspects draws attention to some of the unique problems associated with gold exploration that need to be taken into account in the design and implementation of geochemical techniques appropriate for gold exploration. In the case of geochemical exploration for gold deposits, particular attention needs to be focused on developing and implementing more reliable exploration methodology on account of the unique properties of gold. Whilst the case history examples cited are restricted to Canada and refer to glacial overburden and related soils and stream sediments, the same basic sample representivity requirements apply to all sample media and thus the information is of worldwide significance.

For geochemical exploration for gold deposits to be effective, a number of requirements need to be met as it is by no means a panacea. Mineralization

must occur beneath the sampled material. If mineralization is blind, then little hope exists for geochemical exploration methods to be effective. Similarly, responses related to mineralization need to be present in the sample material, e.g. weathered rock, overburden, or drainage sediment. For success to occur, it is essential that in the design stage attention be paid to sampling, sample processing, analysis, and understanding how to interpret the data. The risks are high and the chances of reward are relatively low using some of the methodology that is prevalent today.

The variability in the size of gold particles, gold concentration, and degree of representivity necessary are fundamental features characteristic of given exploration areas, i.e. features over which there is no control, but which must be taken into account in designing and implementing an exploration program. This applies irrespective of the phase of exploration involved whether it be reconnaissance, possibly involving drainage sediment sampling, or very advanced level exploration involving channel sampling of trenches or even drill core. The fundamental requirement is to obtain an adequately representative sample to meet specific representivity levels. It is to be expected that the representivity requirements would increase through the exploration sequence from reconnaissance through to drilling. Attention must be focused at the outset of an exploration program on undertaking an orientation survey aimed at identifying the nature of gold dispersion associated with mineralization as a basis rather than assuming a particular methodology appropriate in one area will be suited to another area.

The orientation survey should be undertaken with respect to known mineralization and preferably mineralization that is economic or as close to economic as possible. This is due to the fact that only

limited purposes are served establishing responses related to mineralization that is clearly subeconomic and then basing the exploration design on responses related to this type of mineralization. Such an approach would be prone to generating an abundance of anomalies related to non-significant mineralization that would lead to follow-up in unwarranted areas. However, having said this, caution needs to be exercised in placing too much emphasis on the relation between the absolute gold value in stream sediments, for example, and primary mineralization. In the event of different types of gold deposits being known (e.g. different particle size of gold), all types should be sampled to allow the subsequent methodology to be suited to the detection of all types of deposits possibly present in the exploration area.

Orientation sampling should encompass the collection of key samples with known spatial relations to mineralization of the full range of sample types that are perceived to be potentially useful, e.g. complete soil profiles or drainage sediments at varying distance from mineralization. These samples will allow the identification of the appropriate sample interval or sample density to be adopted in a particular phase of an exploration program. In addition to sampling with respect to mineralization, sampling of apparently background areas is equally important as one of the functions of the orientation survey is to establish the diagnostic nature of geochemical responses related to mineralization relative to background areas. Background sampling should include the collection of material from the full range of lithological and surface environments present in the area.

The aspects that warrant attention (only slightly modified from Harris 1982) are shown in Figure 47.14. A key factor concerns the identification of a location or environment where an appropriate sample can be obtained. In areas of deep glacial overburden this is related to identifying topographic lows at the bedrock-overburden interface where lodg-

ment till may be preserved. Similarly, in drainage sediment surveys it relates to where the critical sample type may occur. This may be in high or low energy depositional environments according to whether the gold is expected to be medium or fine grained.

In sampling, a key question is what type of sample contains a reflection of mineralization. In areas of glacial overburden this is normally lodgment till. However, in drainage sediment surveys the appropriate sample type may be very coarse gravel or sand according to the size of gold particles characteristic of the deposit being sought. Similarly, in soil surveys the question to be answered is, what is the optimum soil horizon? In routine surveys every effort needs to be made to ensure that samples are comparable and of the same type. Where this is not possible, the fact needs to be recorded and taken into account during interpretation.

An additional aspect to be considered is how to collect an adequately representative sample that contains a signature reflecting gold mineralization. In the actual collection stage, it may be important that the entire sample is collected as opposed to an essential fraction being lost. This factor is particularly relevant in reverse circulation drilling whereby a considerable portion of fine-grained material is lost and not collected (Averill and Thomson 1981). Investigations have shown the majority of the gold to be located in the fine-grain sized fraction (Nichol and Shelp 1985). Similarly, it may be of critical importance to avoid the loss of the fine-grain fraction of stream sediments if gold is associated with this fraction. In the event of on-site sample treatment frequently undertaken to reduce the weight of sample being transported, care should be taken to ensure that no critical fraction of the sample is lost, e.g. fine grained sized fraction. Furthermore, consideration needs to be given as to how to obtain a representative sample at a given site, e.g. can an adequately representative sample be obtained from a single site or is the local scale variation in the distribution of gold such that a representative sample can only be obtained by collecting a composite sample from several subsites? In a reconnaissance scale drainage sediment program, the existence of considerable variation in gold content was shown to exist over a very short distance in the drainage system (Harris 1982).

As is apparent from the theoretical considerations discussed previously, it is absolutely critical to ensure that a sample of adequate size is collected to provide the necessary representativity. As indicated, the necessary size varies sympathetically with the size of gold particles and inversely with the content of the gold concentration and level of representativity required. Consideration needs to be given to the adequacy of any on-site sample treatment. Loss of any significant gold-bearing component of the sample during sample treatment would obviously be detrimental.

STAGE	FOCUS
SAMPLING	Environment
	Type
	Collection
	Size
SAMPLE PREPARATION	Treatment
	Bulk
	Reduction
	Concentrate
ANALYSIS	Weight
	Replicate

Figure 47.14. Factors to be considered in designing and implementing a geochemical exploration program for gold deposits (modified from Harris 1982).

The underlying purpose of the sample preparation stage is to change the sample collected in the field to a form suitable for analysis. This can be achieved in a number of ways. When samples are prepared, the entire bulk sample collected should be processed to generate as large an *and* homogeneous a sample as possible; i.e. having collected a large sample to meet sample representativity requirements, the processing of a small, unrepresentative subsample which meets the minimum analytical weight requirement should be avoided. The appropriate sample particle size reduction procedure should be examined, e.g. sieving or pulverizing. The classification of a sample into different size fractions by sieving will serve to identify the grain size distribution of gold and the possible advantage of analyzing a particular size fraction. It may be advantageous to examine whether an adequate reflection of the gold content can be obtained by pulverizing the entire sample, so that the gold becomes more evenly distributed in the sample. However, the reduction in size of gold particles poses a problem because of the malleability of gold. In point of fact, what may happen in pulverizing is that the grain size of the gold is reduced by smearing of gold onto other minerals, but if effective this achieves the objective of distributing the gold more evenly throughout the sample. An additional problem may arise from the smearing of gold on the grinding equipment, lowering the content of gold in the sample and creating a potential source of contamination between samples.

A procedure that may be adopted is the preparation of a heavy mineral concentrate from the sample either by field panning or under laboratory conditions. The underlying objective of obtaining a heavy mineral concentrate is to concentrate gold from a large sample into a small enough sample that is representative for analysis. A common procedure, described previously, involves gravity tabling followed by heavy liquid separation. The efficiency of gravity tabling is highly dependent on the particle size of the gold grains and thus it is necessary to ensure that any critical fine-grain sized gold is not being lost during the heavy mineral concentrating process. An important aspect to bear in mind is the limited efficiency of gravitational methods in recovering fine-grained gold, a point long recognized by placer miners. The relevance of this aspect will vary from case to case according to the grain size of the gold.

Following sample preparation, whether it involves sieving, pulverizing, or heavy mineral concentration, the next stage may involve sample splitting to generate a subsample representative for analyses. Care needs to be taken to establish the adequacy of the sample splitting procedure.

With regard to analytical procedures, methods in common usage involve the analyses of 10 to 50 g samples by a variety of procedures. These methods involve adaptations of the traditional fire assay procedures, acid digestion and neutron activation with

actual estimation of the gold content by gravimetry, atomic absorption, plasma or delayed neutron analysis. Within this range of analytical procedures, variations in technique are available to suit individual analytical requirements, e.g. bulk composition of samples, concentration range of interest, accuracy, and precision requirements. For appropriate analyses to be undertaken by a laboratory, it is essential for the geologist or geochemist to discuss the nature of his exploration program and analytical requirement with the analyst to ensure that appropriate analytical procedures are employed. An excellent review of this aspect is given by Burn (1984). In analysis, the size of the sample being analyzed, or alternatively the number of replicate analyses, can be increased within limits but these are very minor considerations compared to increasing representativity relative to sampling and to a lesser extent sample processing.

A system of analytical quality control needs to be instituted whereby it is possible to monitor the representativity of different stages in the exploration sequence. Duplicate field samples, duplicate sample processing subsamples, and samples of known composition can be used to monitor the reliability of sampling, sample processing, and analytical representativity, respectively. This is best achieved by inserting control samples at random. Samples that cover the concentration range expected should be inserted at an overall frequency of some 5 percent. It is important that the sampling and sample processing stages be monitored by submitting for analysis replicate subsamples from each stage. To quote from Burn (1984):

"Control of the quality of sampling and preparation processes is very often a blind spot for many people, who may lavish excessive efforts on checking the assay laboratory but fail to recognize the shortcomings in the preceding stages. Control of assaying is the easier and more obvious procedure to implement. Even so, however it is carried out, if it is not backed by control in the preceding stages, its results can lead to unjustified confidences in the reliability of the assaying data. In the worst cases very precise, accurate and trustworthy assays may be produced by the analyst, from the small subsamples he has received, which bear little relevance to the values of the samples from which they were originally derived."

With regard to the interpretation stage, it is important that consideration is given to identifying criteria by which to evaluate the possible relation of data to mineralization as opposed to solely identifying zones of highest metal content. In particular, consideration needs to be given to the type of sample, and character of the surface environment that the analytical data relate to. Meaningful interpretation of data can only be achieved when due consideration is taken of the geological factors contributing to or controlling the data.

However, adoption of an exploration method should also take into account non-technical features such as: a) financial resources; b) time constraints;

c) personnel; d) equipment; e) accessibility; and f) past experience. In this way, the exploration methodology will represent a compromise between the technically desirable and the economically practicable. Nevertheless, it is critically important to know the confidence that can be placed in the results and by the same token their limitations. The cost of an orientation survey in relation to the total cost of an exploration program is small, and a cost that repays the initial investment handsomely in the sense that it provides critical information at the outset that allows the formulation of an appropriate exploration program.

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48. Evaluation of Unconventional Methods of Geochemical Exploration

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ABSTRACT

Many fields in geochemistry, such as fluid inclusions and stable isotopes, are not being used in exploration for ore deposits. They are thought of as academic or viewed as a means of gaining information on ore formation rather than as part of an exploration approach. This is understandable because it is frequently difficult for the explorationist to see how these techniques can be applied. They tend to be single technique studies in which one topic is considered to the exclusion of others.

Our studies demonstrate that these techniques, when integrated with field data, can be used to optimize an exploration approach and identify priority targets. We have utilized this integrated approach in determining the relationship of surface veining to buried mineralization in West Germany and evaluat-

ing the exploration criteria for Carlin-type gold deposits.

In several areas of West Germany, quartz-lead-zinc veins are exposed. If a genetic relationship can be demonstrated between certain veins and stratiform mineralization, this would represent a breakthrough in prioritizing exploration areas. Applying a combination of fluid inclusion, lead isotope, and EQ3/EQ6 modeling studies to investigating remobilization from the Meggen lead-zinc stratiform sulphide ore, veins related to remobilization can be discriminated from veins which formed as sweatouts during regional metamorphism of black shale.

A similar approach allowed us to determine the geochemical and geologic parameters required for the formation of Carlin-type deposits. Based on this study, exploration criteria for these deposits can be ranked and prioritized and geologic signatures for exploration outside of the Great Basin determined.

Application of Geophysics and Geochemistry to Groundwater and Geothermal Studies



Colour Folio

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8.1(a)



8.1(b)

Plate 8.1. Colour ratio composite (CRC) Landsat images of the Goldfield, Nevada area. 8.1(a) is an MSS image (80 m), composited as MSS 617-green, 516-blue, and 415-red. The green area near Goldfield (see upper arrow) substantially matches a previously compiled map of alteration from field studies. Mafic rocks appear generally white, felsic rocks pink, playas blue, and vegetation orange. 8.1(b) is a TM image (30 m) composited as TM 311-green, 413-blue, and 517-red. The upper arrow, which points to the same area of limonitic alteration shown in the MSS image on the left, indicates by its yellow colour that clay mineral absorption is also being detected. The lower arrow points to the Cuprite mining area where non-limonitic alteration is interpreted from the red colour because the only spectral feature is the $2.2 \mu\text{m}$ clay absorption. The figure illustrates the utility of the MSS system for mapping limonite and the considerable advantages of the higher spatial resolution and spectral information of the TM system.

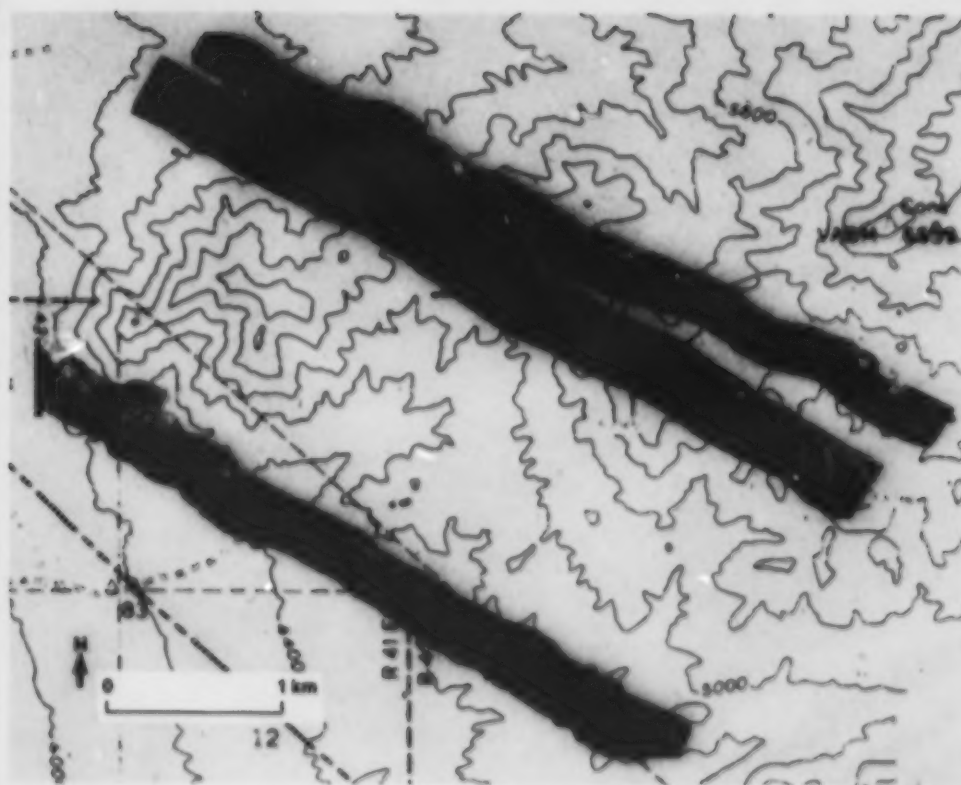
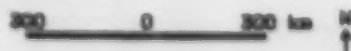


Plate 8.2. A colour composite image displaying mineralogical differences from airborne imaging spectrometry (AIS) of an area in the Grapevine Mountains, Nevada and California (Kruse, in press). The identified minerals and position of the diagnostic spectral bands are: limestones as red ($2.34 \mu\text{m}$), dolomites as yellow ($2.32 \mu\text{m}$), sericite and muscovite as green ($2.346 \mu\text{m}$), and kaolinite as blue ($2.16 \mu\text{m}$). The saturation and value of the colour is determined by the width of the spectral feature and its depth. The image has been co-registered to a 1:24 000 scale map using a digitizing camera. The display illustrates the power of this type of data with appropriate analysis for field studies. The volume of data involved (roughly 34 megabits/line) and the complexity of processing will limit its use to well-defined targets.

Plate 8.3. A colour composite of NOAA-AVHRR data of the Arabian Peninsula. Thermal inertia is coded red, spectral emissivity difference blue, and vegetation index green. The colour display distinguishes differences particularly among the unconsolidated materials. Spatial colour patterns are suggestive of areas where different geologic processes have occurred.



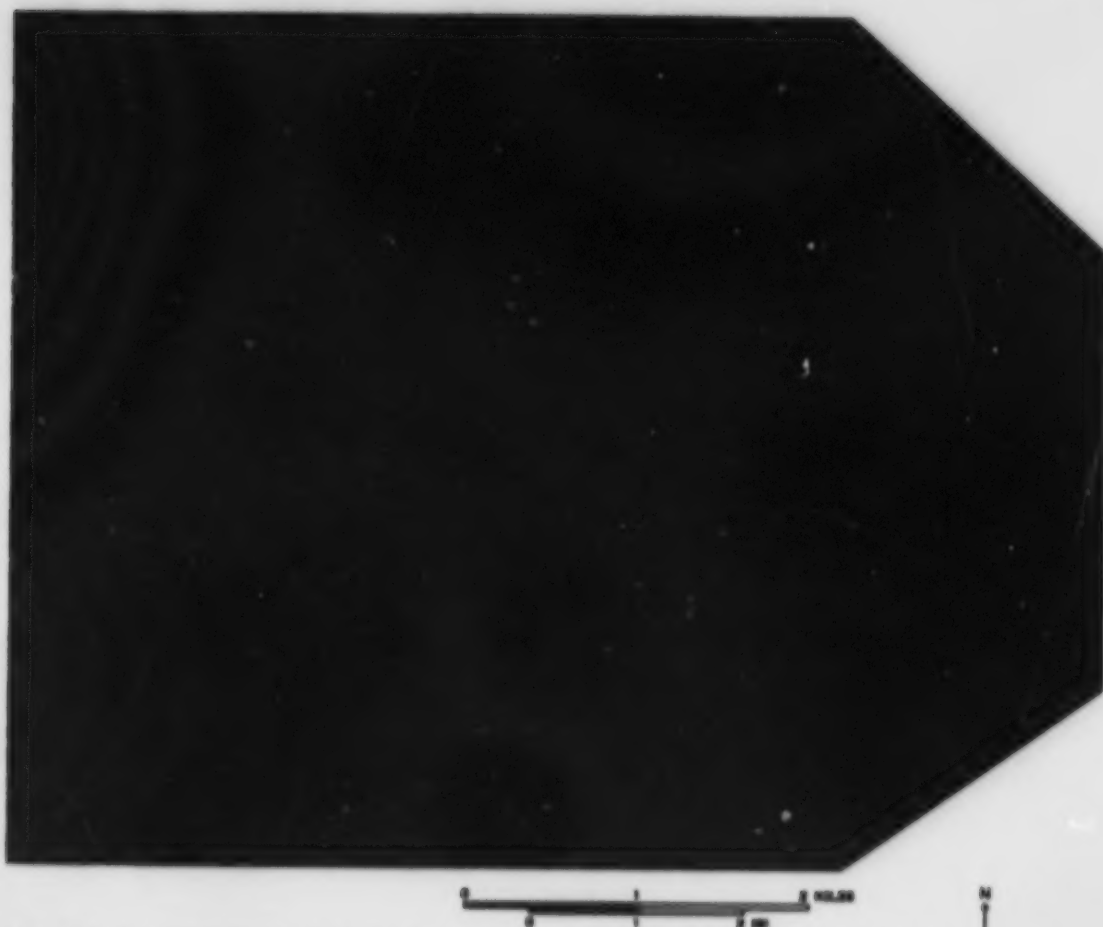


Plate 8.4. A colour decorrelated thermal image of the Carlin, Nevada, gold mine area from the TMS system. Colour differences are generally related to spectral emissivity differences and the image has been co-registered to a geologic map for follow-up field studies. Letters in parentheses in this text correspond to those on the image. The red anomalies coincide with disturbed ground around the mine (M) and silica-rich rocks — primarily quartzite (A). Quartz latites (B) on the western part of the image can be clearly distinguished as can the disturbed areas of the mine. Carbonates (C), which are spectrally neutral in these bands appear green on the composite. Colour differences that imply compositional changes can be seen in a mapped jasperoid unit (D), within the predominantly carbonate assemblages (E), and within a fanglomerate unit (F).



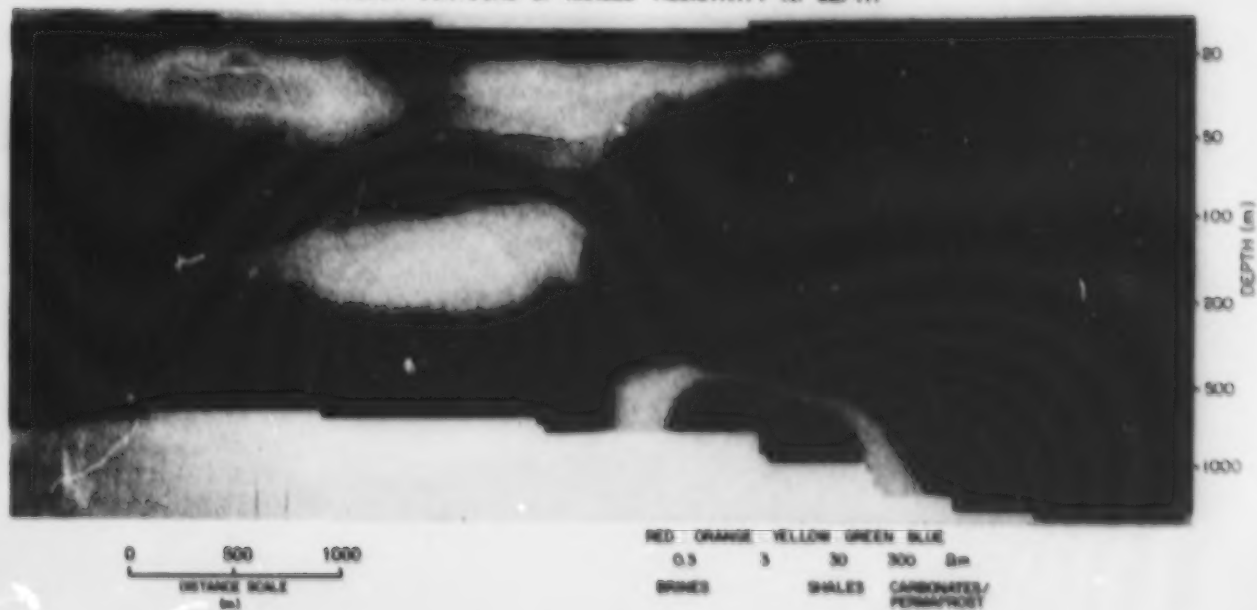
Plate 13.2. An imaged conductivity section obtained over the Ivanhoe Lake Cataclastic zone with the UTEM system showing depth penetration capability in excess of 10 km in an area with crustal resistivities in excess of 10 000 Ωm (Kurtz et al. 1988).

Plate 11.1. Helicopter-borne geophysical system including cesium magnetometer/gradiometer, three frequency electromagnetic system, VLF and 1024 channel gamma spectrometer system.



Plate 13.1. The imaged conductivity-depth section derived from Figure 13.8 data. Red colours indicate resistivities less than $3 \Omega m$, the green-yellow colour boundary is at $30 \Omega m$, and blue indicates resistivities in excess of $300 \Omega m$.

COLOUR CONTOURS OF IMAGED RESISTIVITY vs. DEPTH



CONDUCTIVITY

INSIDE BAR 1-4175 Hz

OUTSIDE BAR 1-32 kHz

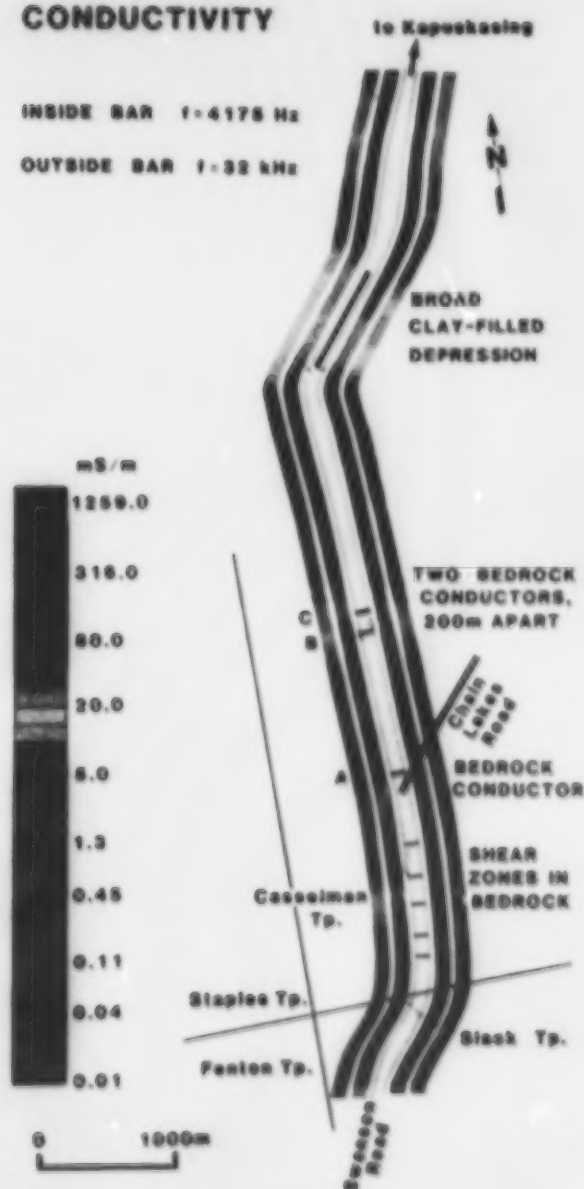


Plate 15.1. Colour bars depict changes in apparent conductivity along the Kapuskasing Transect (segment 4, 35 km south of Kapuskasing), Ontario, Canada. Conductivity was calculated from the horizontal coplanar helicopter AEM data (inside bar 4175 Hz, outside bar 32 kHz) using a thick horizontal layer model. Annotated features were checked in the field by ground surveying and drilling.

DEPTH TO BEDROCK

INSIDE BAR 1-4600 Hz

OUTSIDE BAR 1-32 kHz

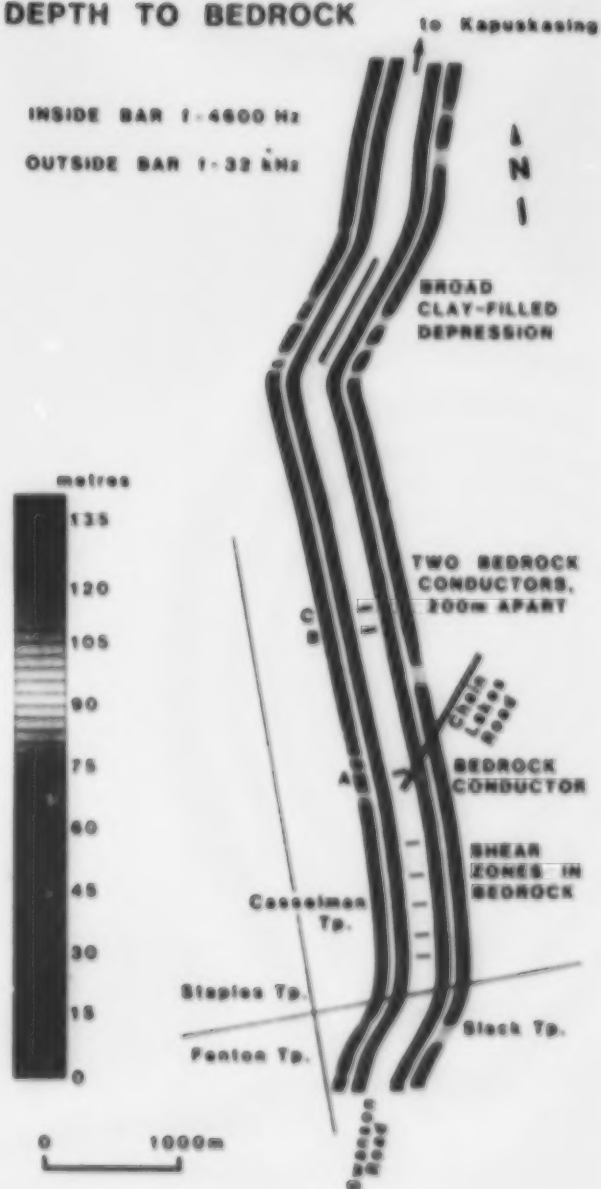


Plate 15.2. Colour bar map of depth to bedrock compiled from horizontal coplanar AEM data (inside bar 4600 Hz, outside bar 32 kHz). Segment 4 as in Plate 15.1.

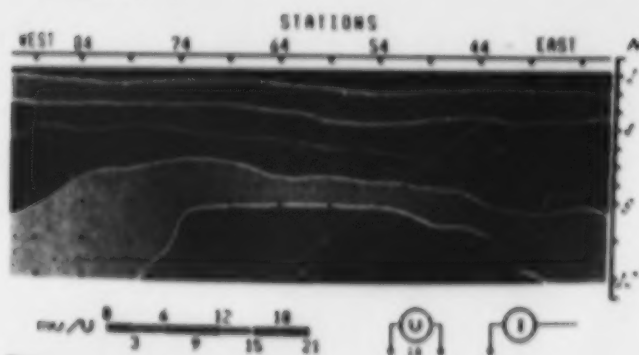
CHARGEABLE EITV
TELLURIC CANCELLEDPULSE = 2.5 Sec.
100500 FL (152 M)THOMAS PROJECT, NEVADA
LINE 2

Plate 18.3. Telluric cancelled IP pseudo section at 2.5 seconds pulse length, Thomas Project, Line 2, showing anomaly due to deep sulphide body.

CHARGEABLE EITV

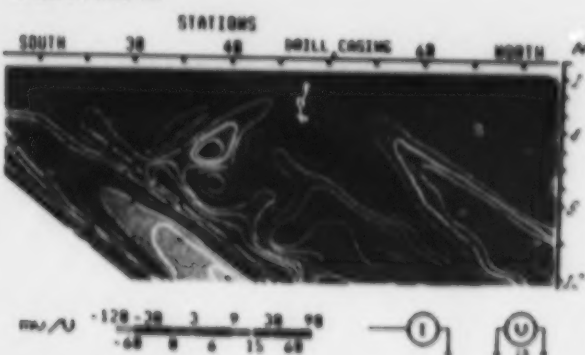
PULSE = 25 Sec.
100500 FL (152 M)HALL PROJECT, NEVADA
LINE 1

Plate 18.5. IP pseudo section at 25 seconds pulse length, Hall Project, Line 1, showing severe spurious "anomalies", due to telluric noise, that trend along the current diagonals.

HALL PROJECT, NEVADA
LINE 1

CHARGEABILITY MEASURED
TELLURIC CANCELLED
7.5/25 Sec. PULSES
2-100 Ft (30 M)

HALL L., NE UGANDA
LINE 1



Plate 18.7. Pseudo section showing ratio of telluric cancelled chargeabilities at 7.5 and 25 seconds pulse lengths, Hall Project, Line 1. Except for drill-stem-casing responses, high ratios indicate that IP response of geologic materials measured by line drops rapidly as pulse length is increased.

RESISTIVITY
PULSE 25 Sec.
2-100 Ft (30 M)

PINSON GOLD MINE
NE UGANDA
LINE 1

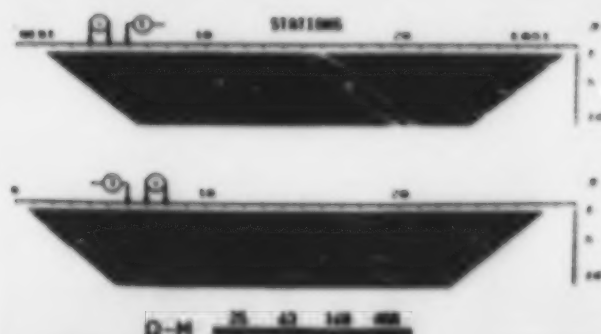


Plate 18.9. Resistivity pseudo sections, Pinson Gold Mine, Line 1: dipole-dipole and pole-dipole arrays.

GEOLOGIC CROSS-SECTION

PINSON GOLD MINE
NE UGANDA
LINE 1

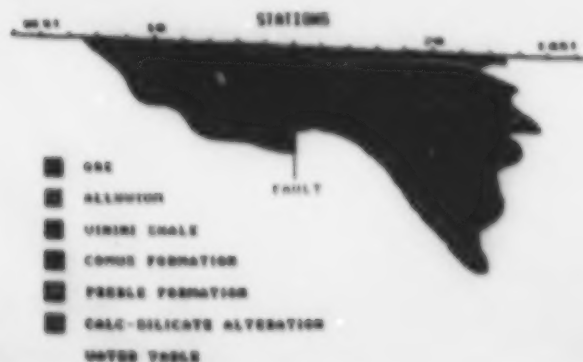


Plate 18.8. Geological cross-section of the Pinson Gold Mine at location of Line 1.

CHARGEABILITY
PULSE 25 Sec.
2-100 Ft (30 M)

PINSON GOLD MINE
NE UGANDA
LINE 1

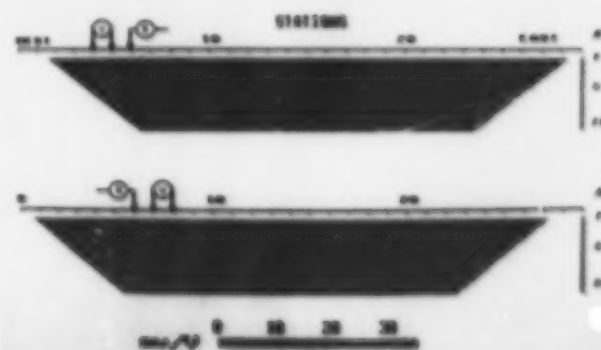


Plate 18.10. IP pseudo sections at 25 seconds pulse length, Pinson Gold Mine, Line 1: dipole-dipole and pole-dipole arrays. Chargeability-high anomaly on each pseudo section is caused by black shales in the Vinini Formation.



Plate 18.11. Model cross-section of Pinson Gold Mine at Line 1, based on modeling of dipole-pole and pole-dipole resistivity and IP data sets. The resistivity-high anomalies are due to the Comus Formation (the ore host), and zones of calc-silicate alteration zones within the Comus Formation.

CHARGEABILITY
PULSE 25 Sec
a 100 Fm (328 ft)

QUARTZ MOUNTAIN GOLD DEPOSIT
CLASS. 33 343 MGE
CHARGEABILITY
LINE 1

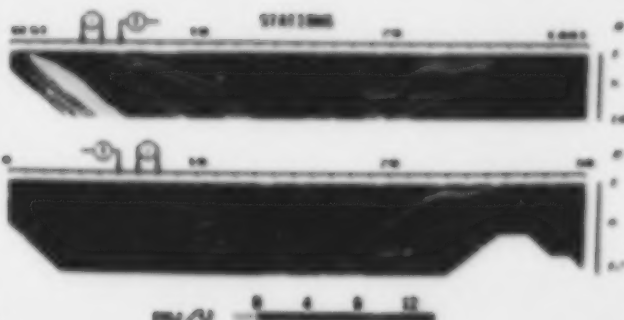


Plate 18.13. IP pseudo sections of Quartz Mountain gold deposit, Line 1: dipole-pole and pole-dipole. Chargeability-high anomalies are caused by two flat-dipping, gold-bearing units containing pyrite.

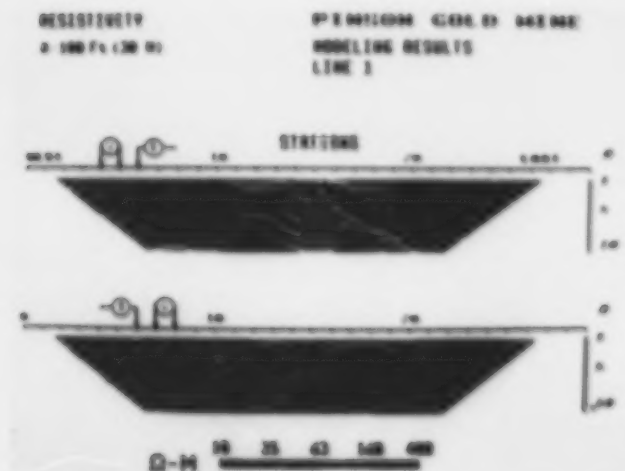


Plate 18.11. Model resistivity pseudo sections of Pinson model cross-section, Line 1: dipole-pole and pole-dipole.

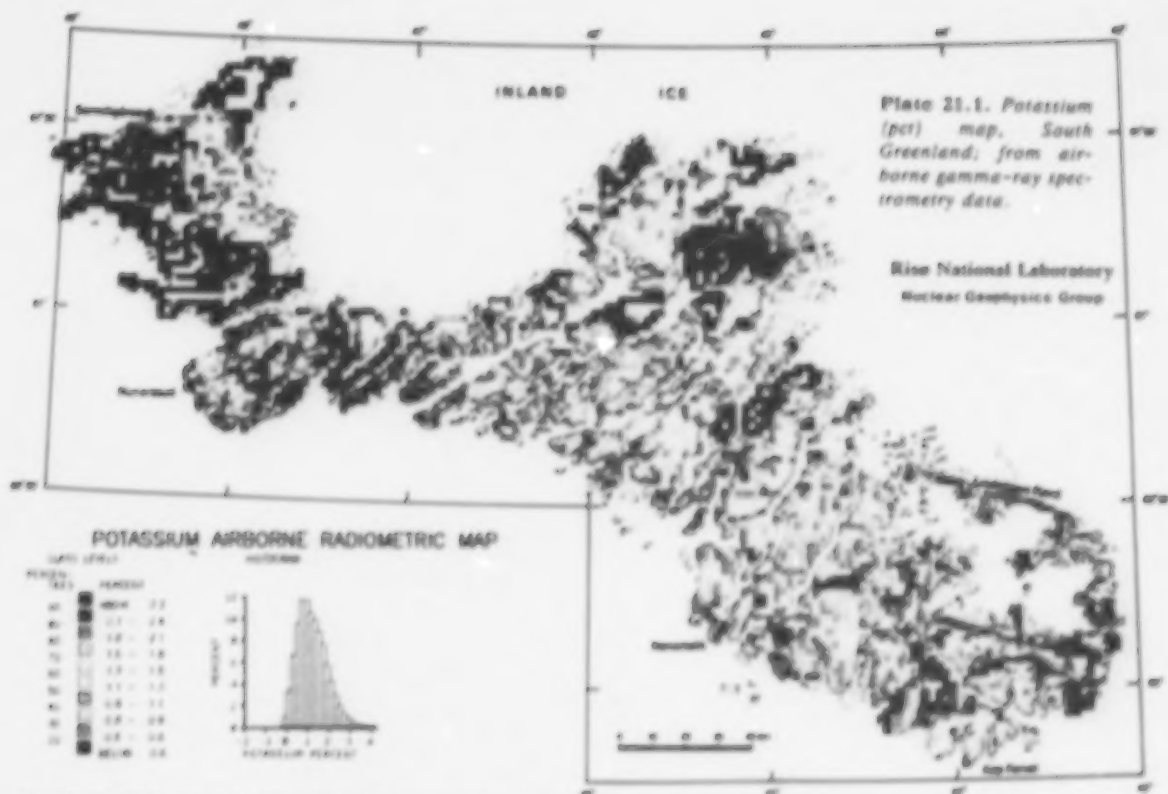
Plate 20.3. Log-residual colour composite image from Airborne imaging spectrometer data of the Oatman area in Arizona. The wavebands are 2.16 μm in blue, 2.20 μm in green and 2.33 μm in red. The image brightness values are inverted so the absorption in each band appears bright.



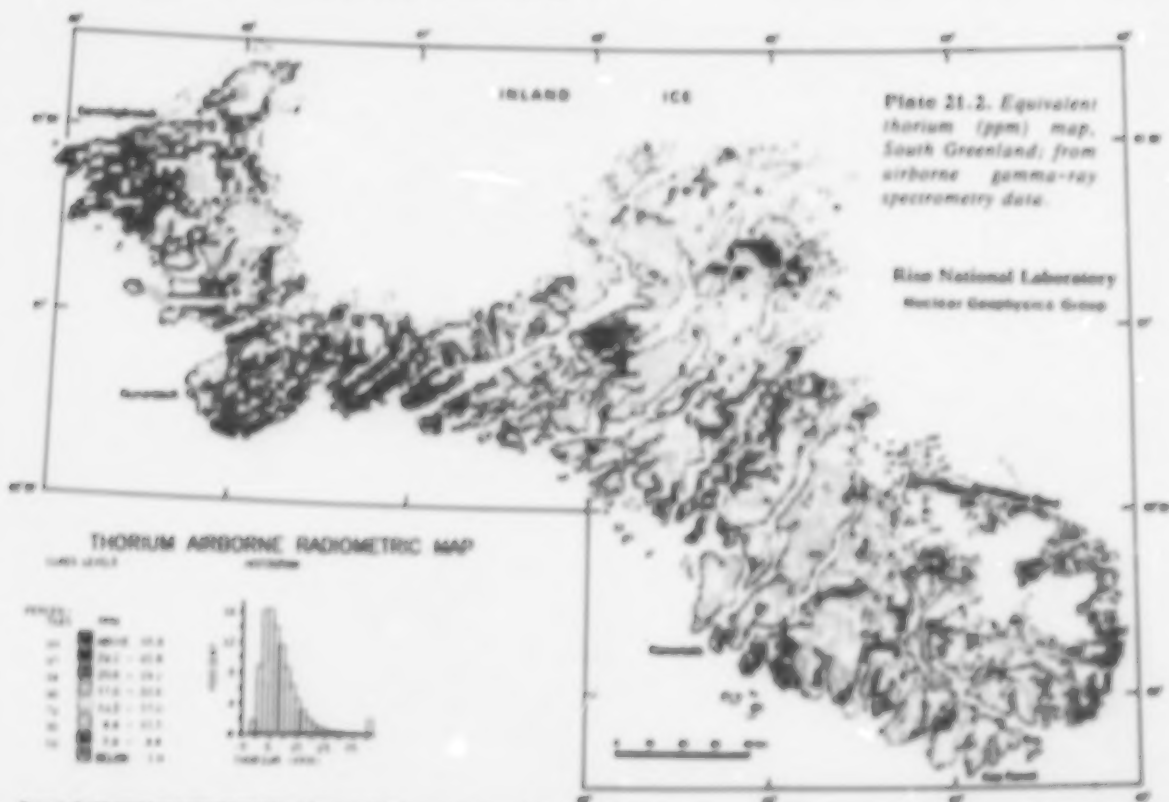
Plate 20.1. Landsat TM colour ratio image of the Yerington mine in Nevada. The image has the $0.8 \mu\text{m}/1.6 \mu\text{m}$ ratio in blue, the $0.65 \mu\text{m}/0.5 \mu\text{m}$ ratio in green, and a residual image enhancing clays in red.



Plate 20.2. Airborne Thematic Mapper colour ratio image of an area east of Christmas Well, near Leonora, Western Australia. The image has the $0.8 \mu\text{m}/1.6 \mu\text{m}$ ratio in blue, the $0.65 \mu\text{m}/0.55 \mu\text{m}$ ratio in green, and the $1.6 \mu\text{m}/2.2 \mu\text{m}$ ratio in red.



Prepared by The Geophysical Service of Canada, Rice National Laboratory and The National Institute of Standards, 1987



Prepared by The Geophysical Service of Canada, Rice National Laboratory and The National Institute of Standards, 1987

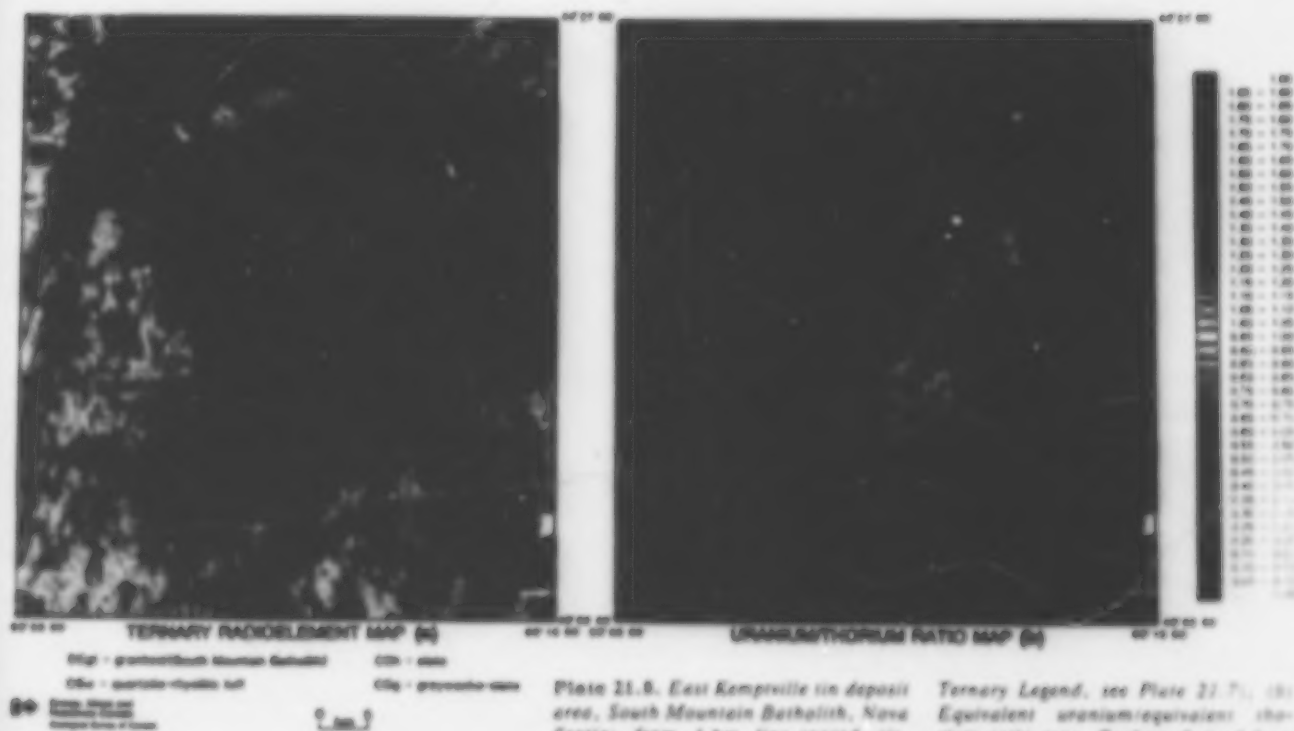
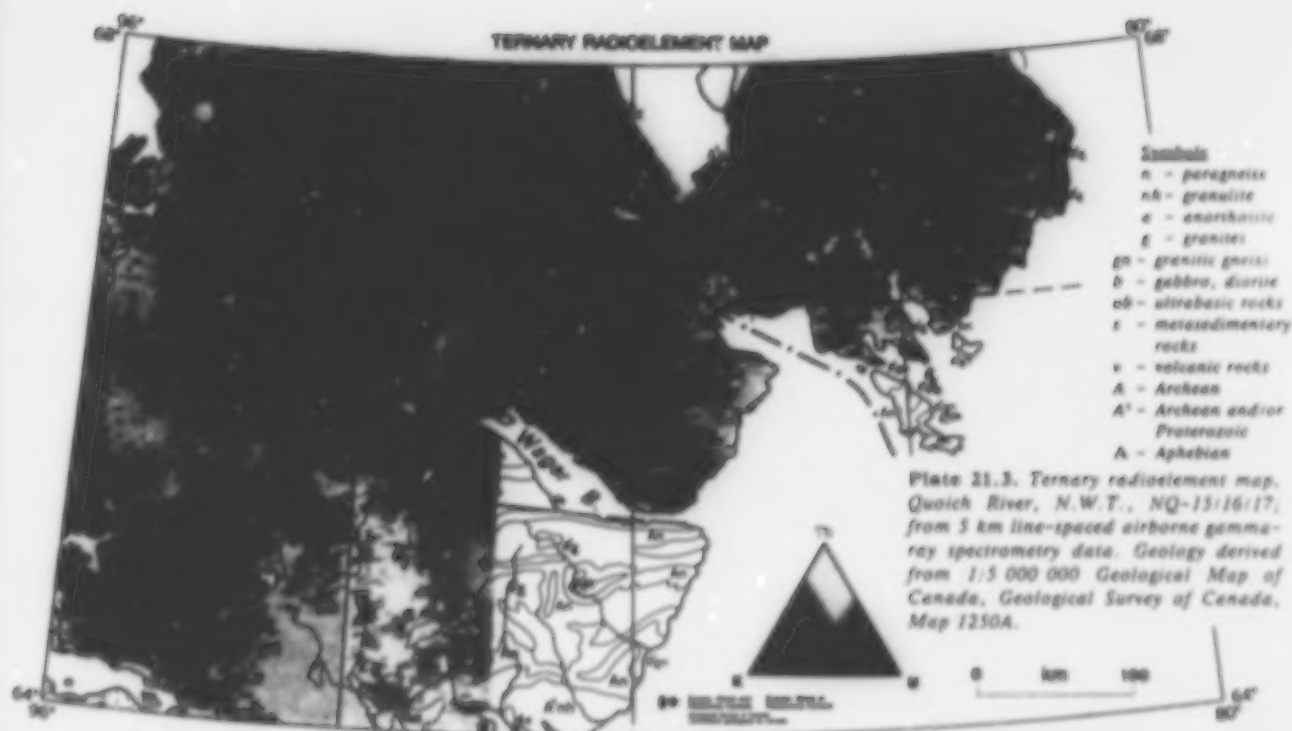


Plate 21.4. Potassium (pct) map, mainland Nova Scotia; from 1 km line-spaced airborne gamma-ray spectrometry data.

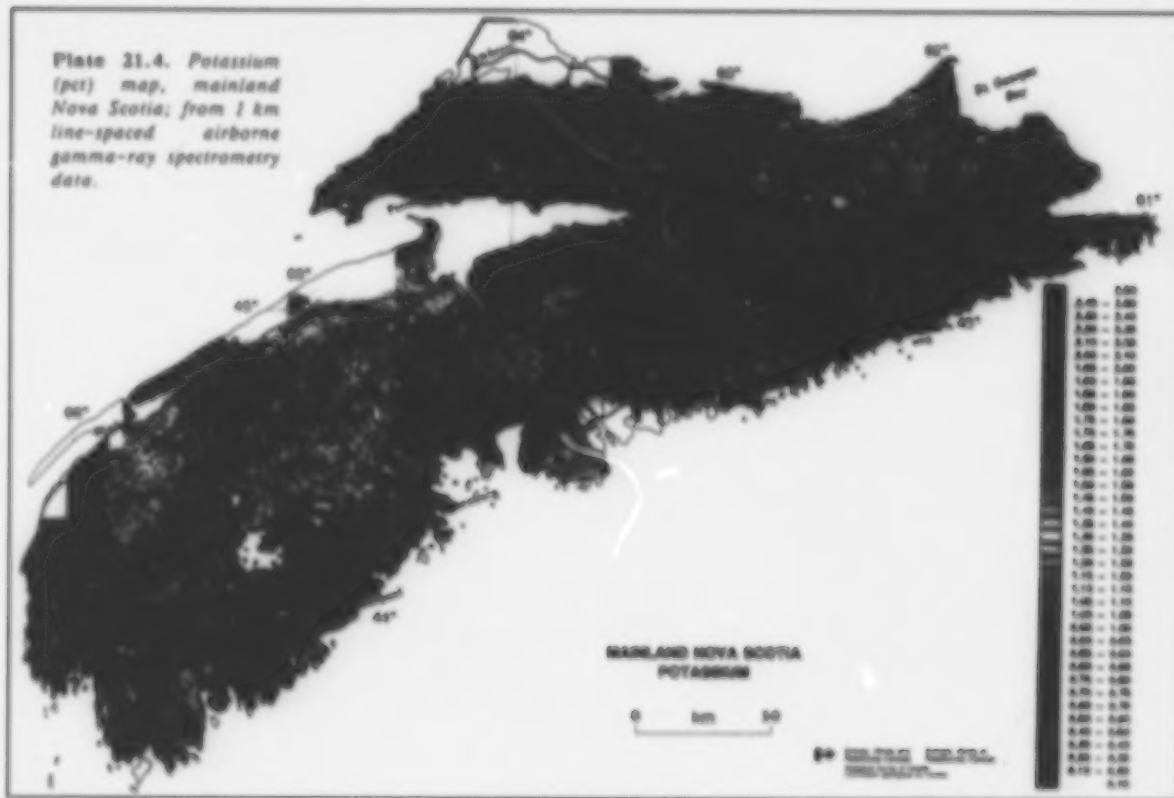


Plate 21.5. Equivalent thorium/potassium ratio map, mainland Nova Scotia; from 1 km line-spaced airborne gamma-ray spectrometry data.



Plate 21.6. Ternary radioclement map, mainland Nova Scotia; from 1 km line-spaced airborne gamma-ray spectrometry data.

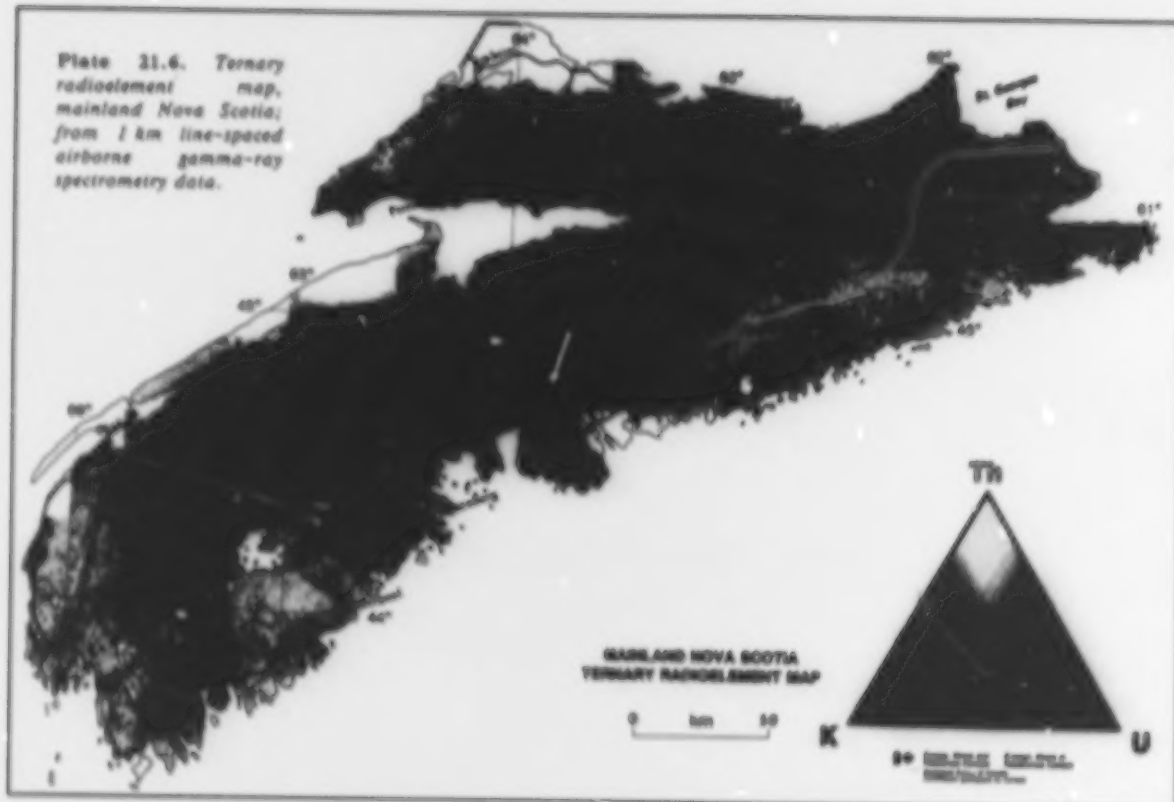
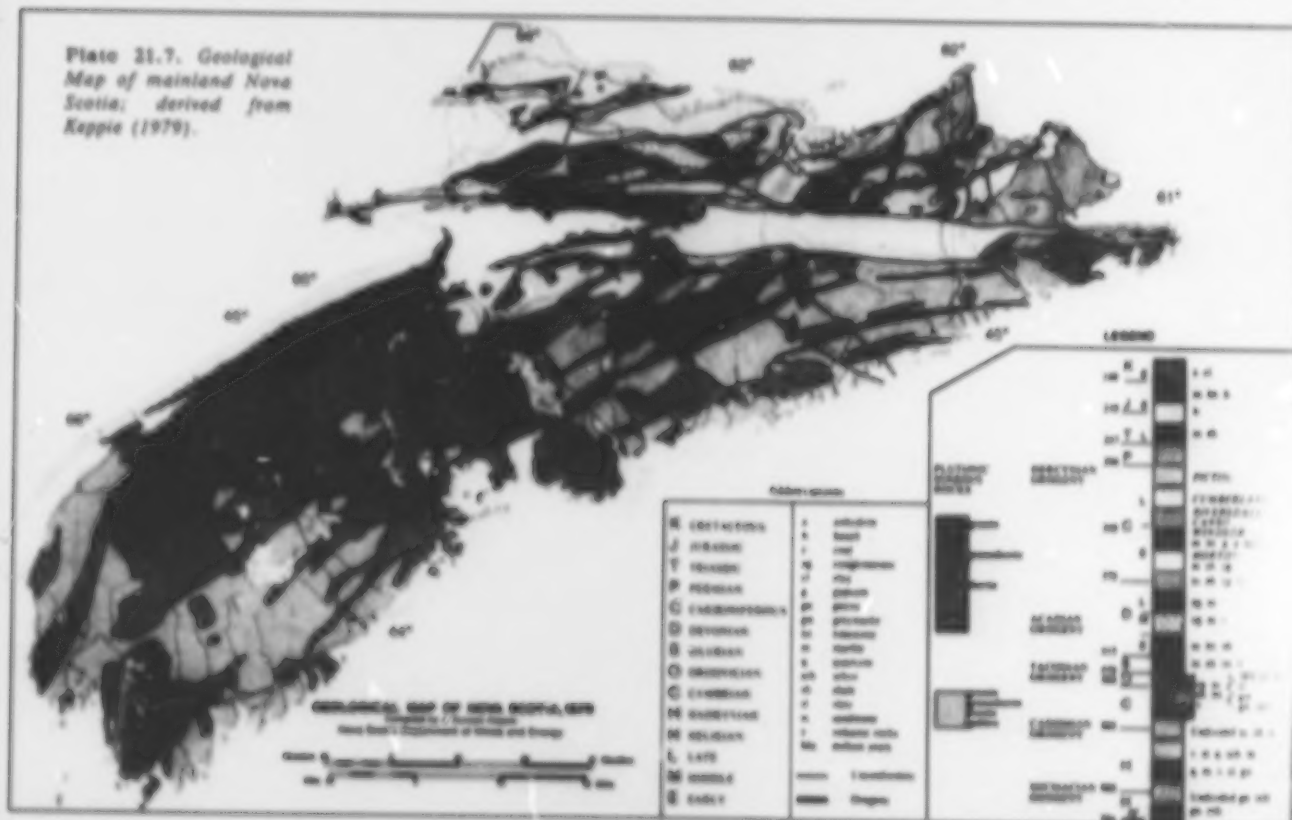
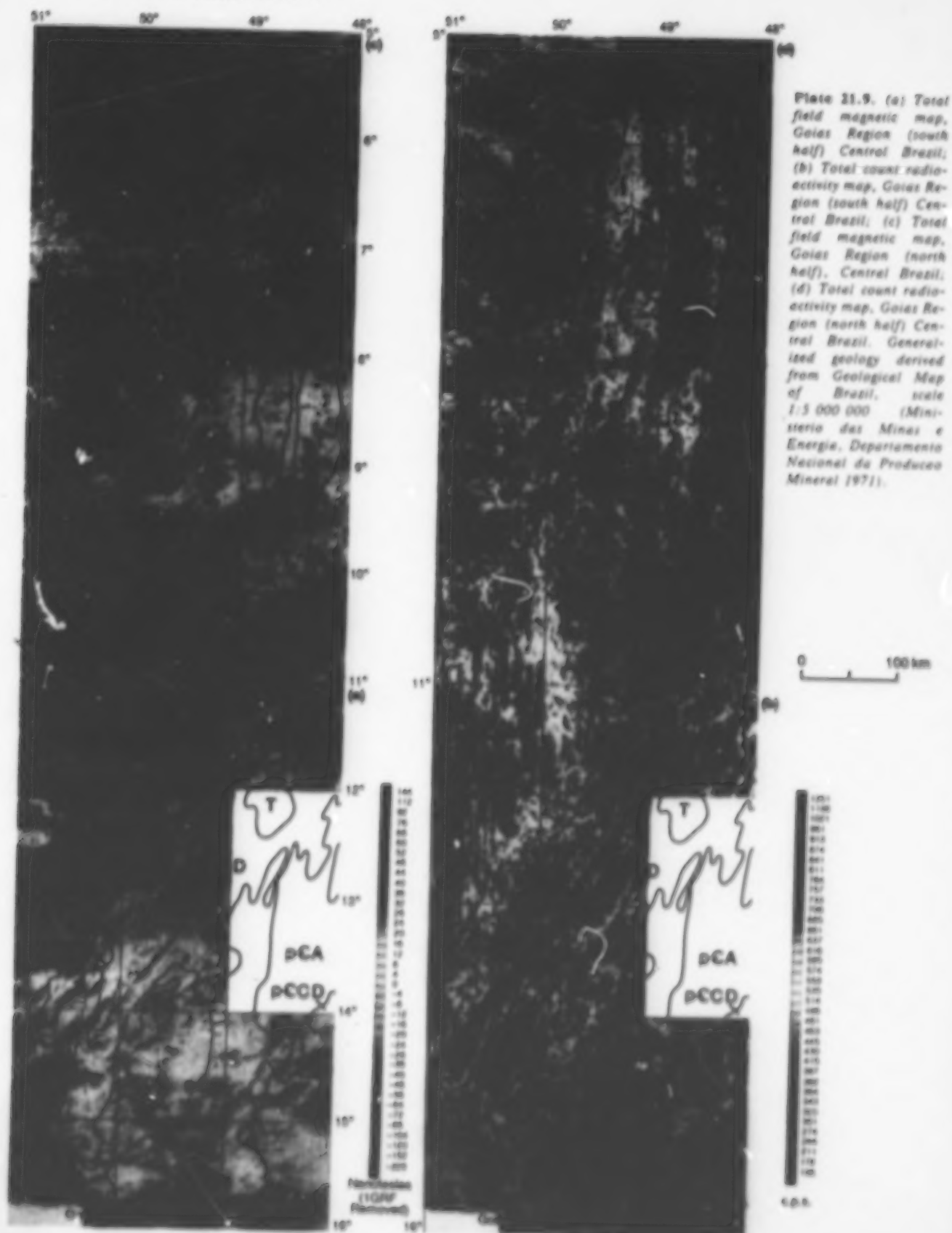


Plate 21.7. Geological Map of mainland Nova Scotia; derived from Kappie (1979).





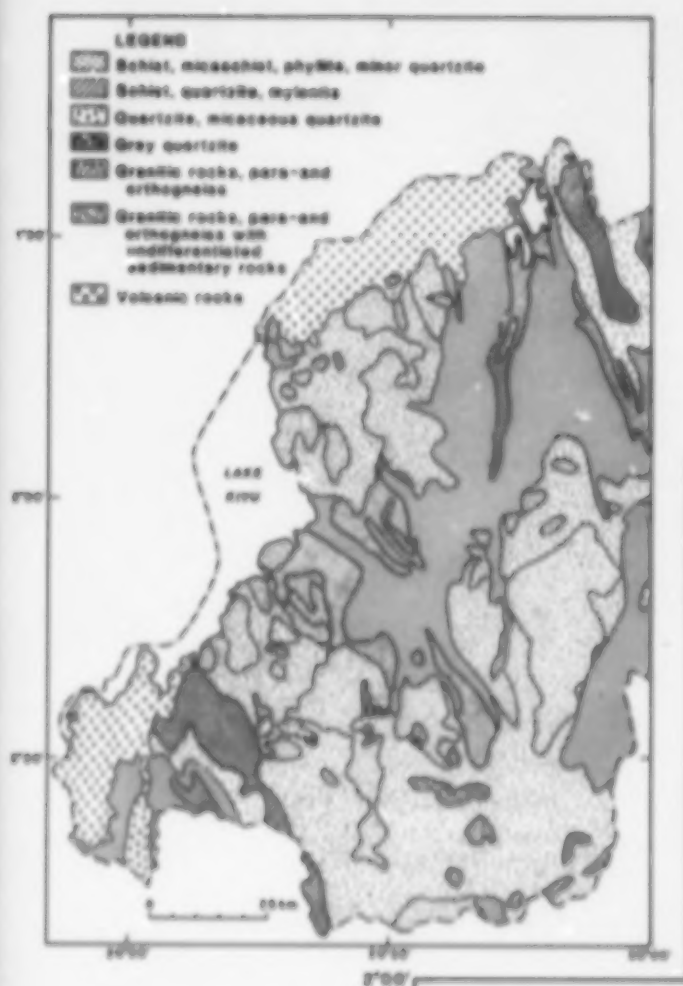


Figure 21.3. Generalized geology, Rwanda (western half), derived from *Institut Géographique National de Belgique* (1981).

URQUHART DYERSON LIMITED
THREE-COMPONENT RADIOMETRIC MAP
OF THE
REPUBLIC OF RWANDA
1:500,000
DATA COLLECTED BY ROBERT MURPHY IN COOPERATION WITH I.C. S.A. FOR THE BENEFIT OF MINERAL & EARTH COUNCIL PROJECTS OF THE MINISTRY OF



Plate 21.16. Ternary radiometric map, Rwanda (west half); from 500 m line-spaced airborne gamma-ray spectrometry data (Republic of Rwanda 1988).

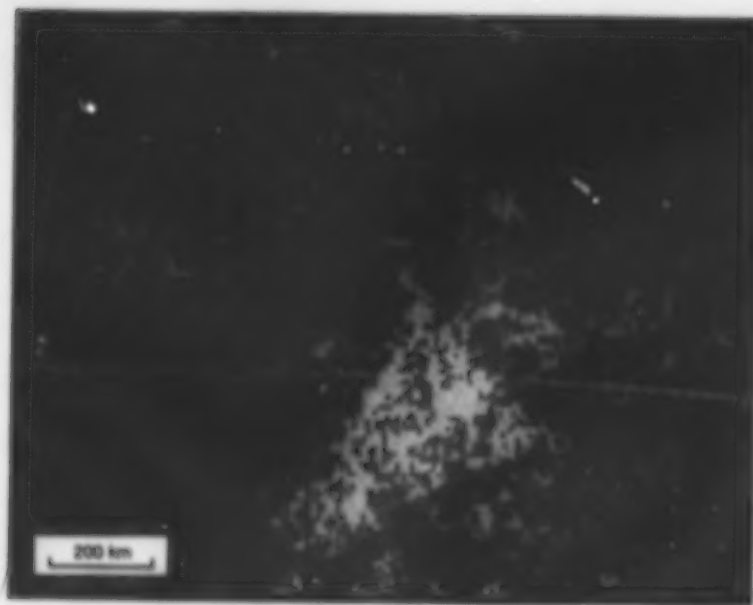


Plate 23.1. Magnetic anomaly colour map, central southern China (Lin Qiao, personal communication) for the area indicated in Figure 23.3. Meridian is 110°E. Parallel is 30°N.

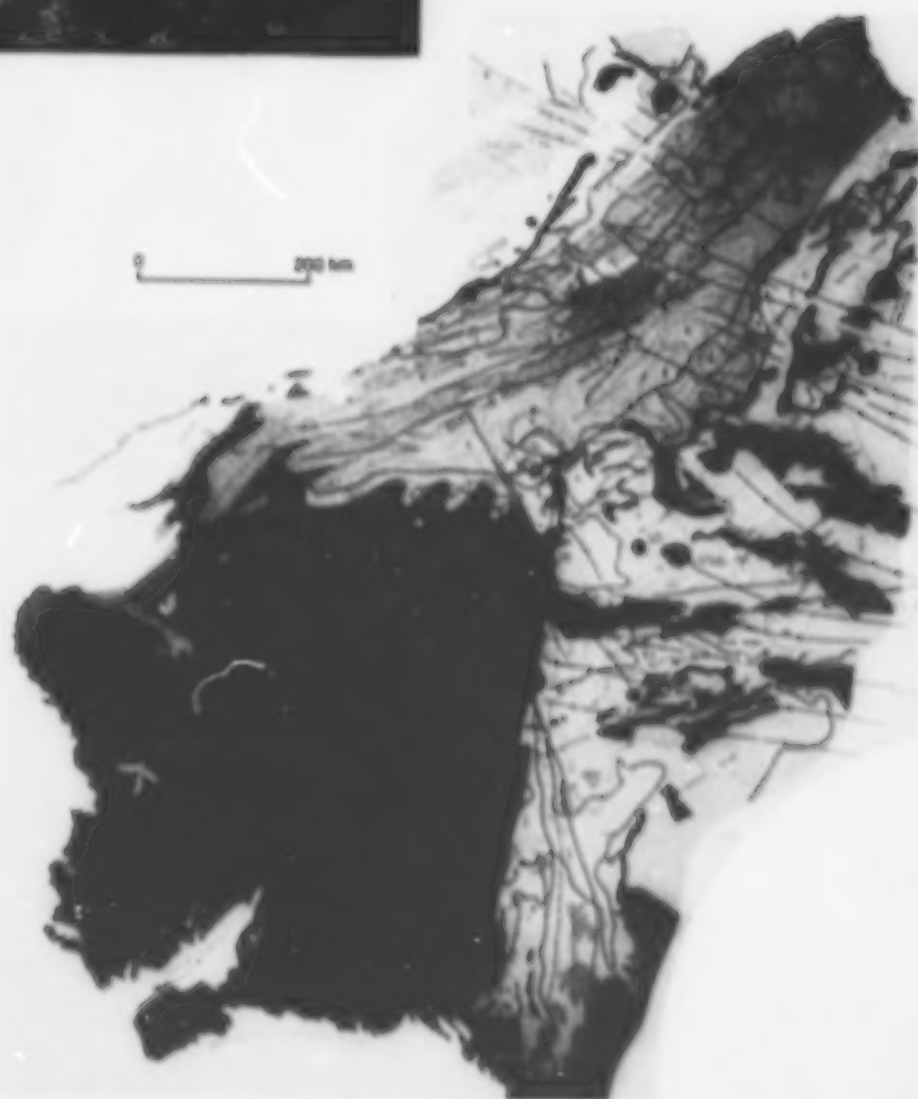


Figure 23.2. Geological framework of western Botswana and adjacent areas, compiled from the reconnaissance aeromagnetic series of Botswana, and outcrop and borehole data in Botswana, and from published maps and reports in Namibia and South Africa (reproduced at reduced scale from Meisner and Peart 1986; courtesy of the Botswana Geological Survey).

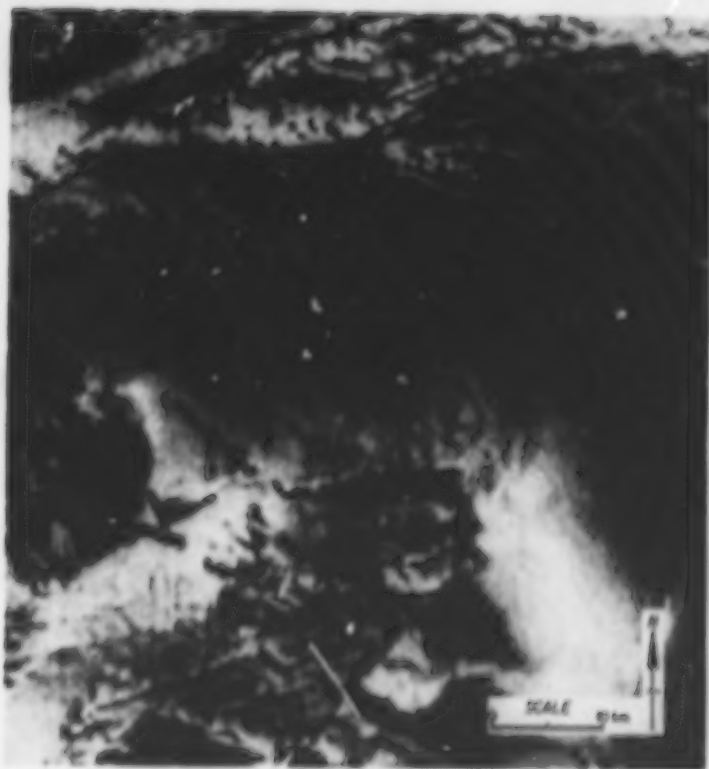


Plate 24.1. Shadow map of magnetic total field from digitally recorded high-sensitivity survey, Minnesota. Courtesy of Dataplotting Services Incorporated, Toronto (after Chandler 1983).



Plate 24.2. Image analysis of aeromagnetic data using IBM-PC microcomputers.

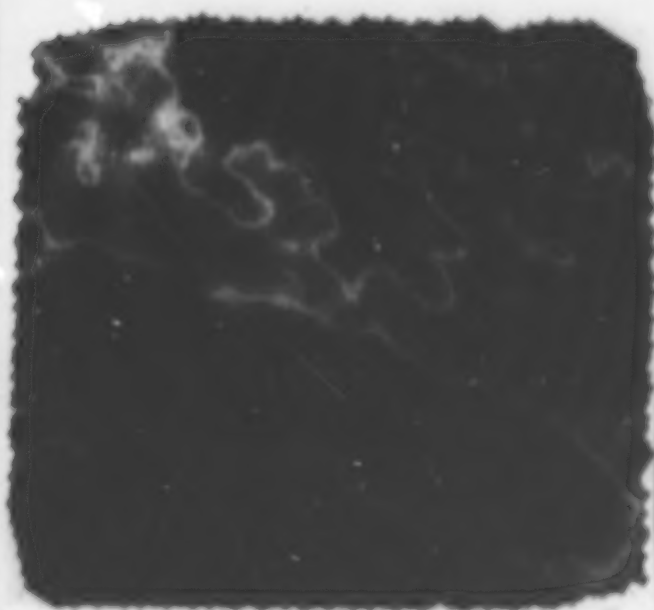


Plate 24.3. Total magnetic field: Burkina Faso (after Paterson 1985).

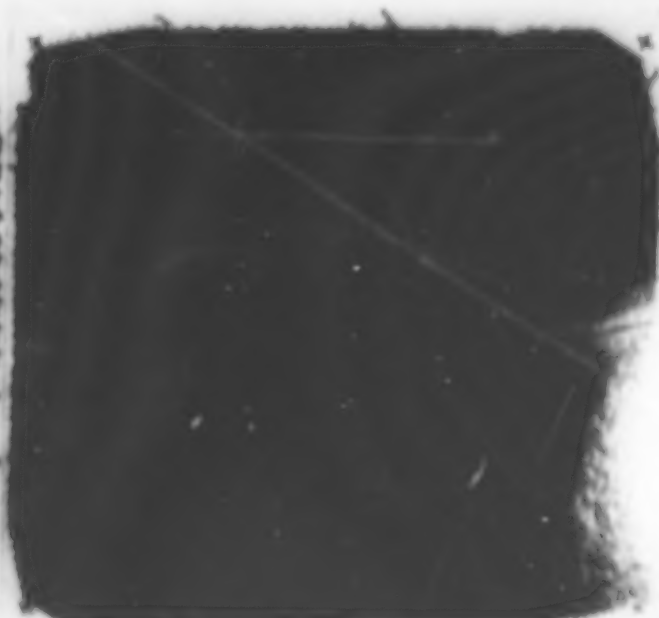


Plate 24.4. Contours of depth to magnetic basement and individual anomaly calculations: Burkina Faso.

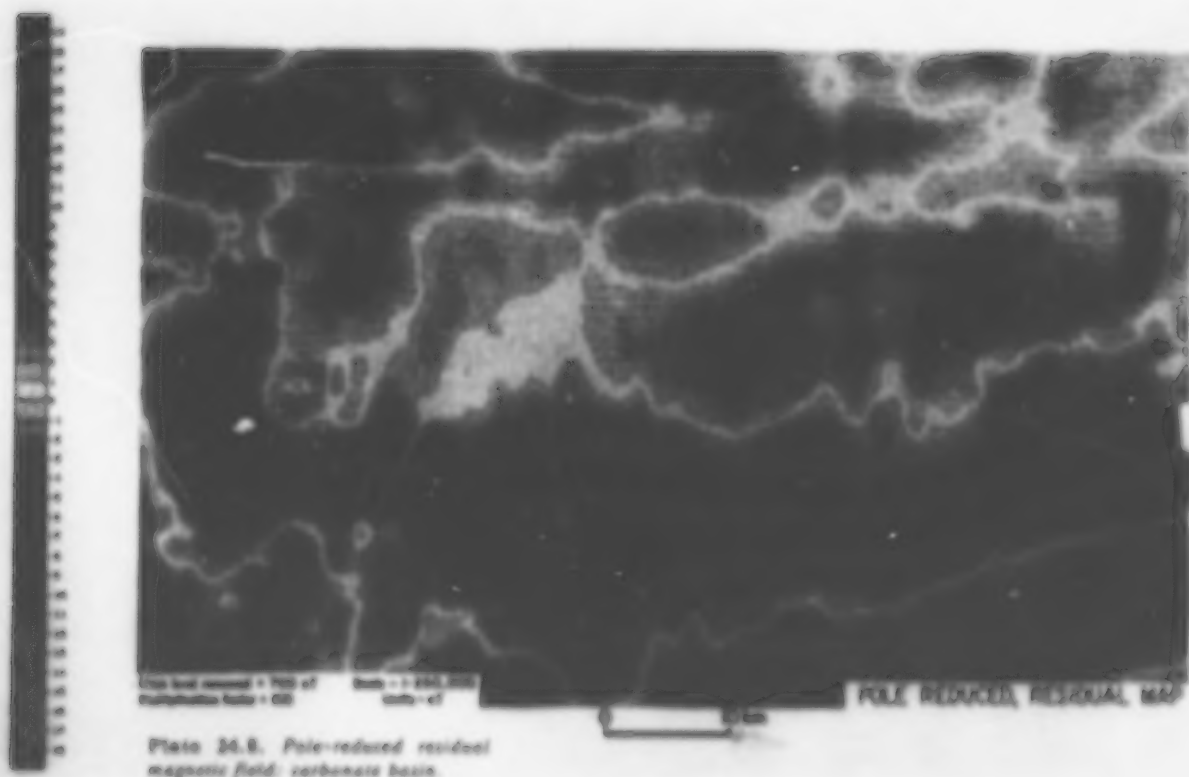
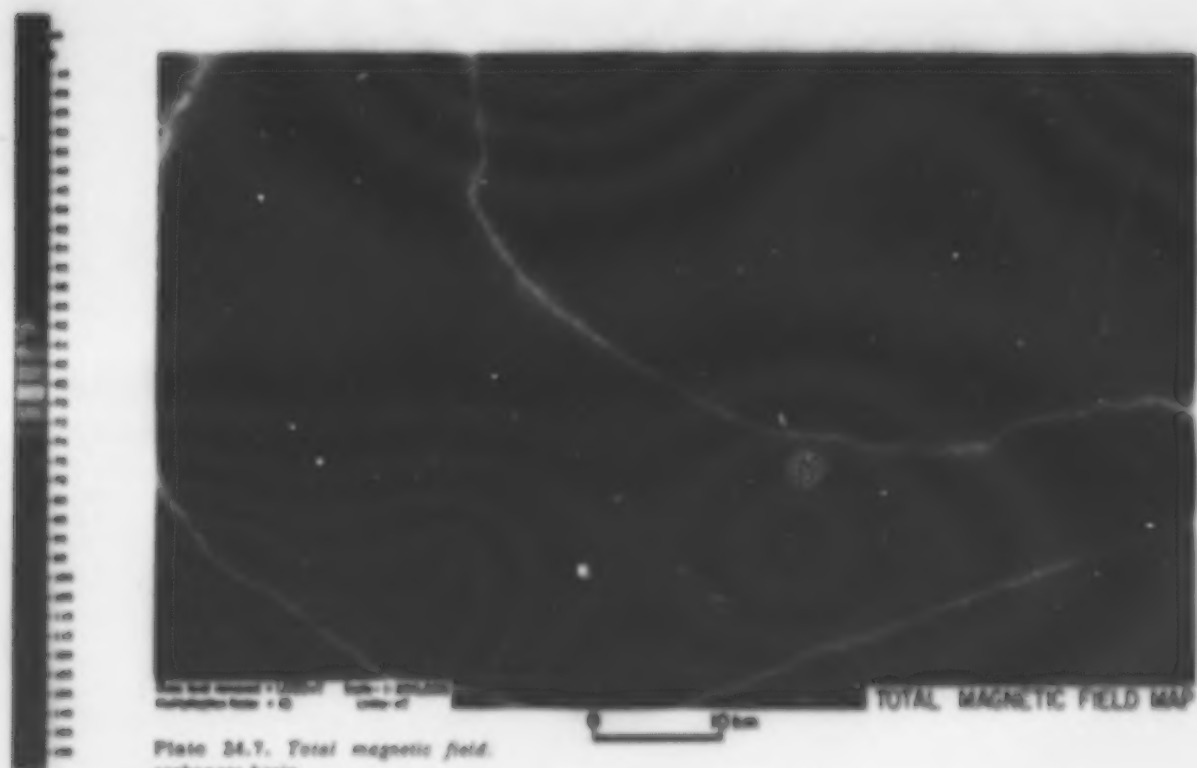




Plate 24.9. Pole reduced, residual, downward continued, first vertical magnetic derivative map: carbonate basin.

0 10 km

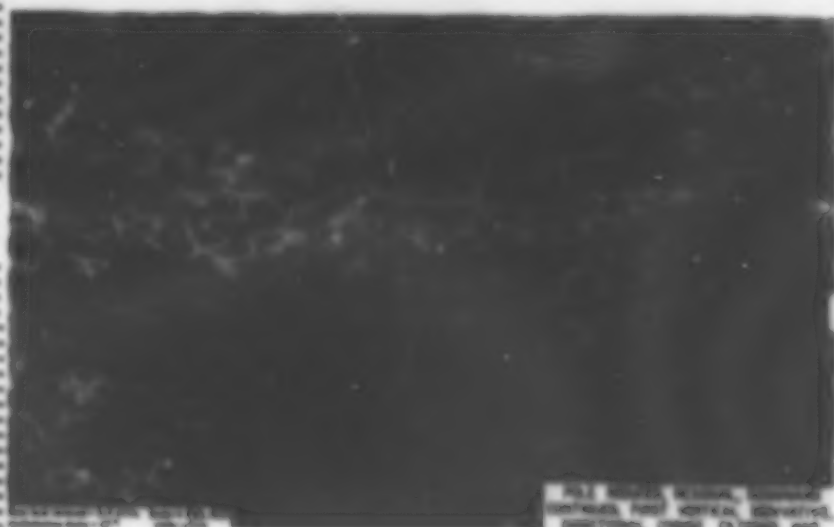


Plate 24.10. Pole reduced, residual, downward continued, first vertical derivative, directional cosine filtered magnetic map: carbonate basin.

0 10 km



Plate 24.11. Structural-geological interpretation of calculated enhanced magnetic map (Plate 24.10): carbonate basin.

0 10 km



Plate 24.9. Total magnetic field, Northwest Territories, Canada, flight line spacing 400 m, flight elevation 130 m. 30 (00) is removed.



Plate 34.6. Apparent magnetic susceptibility map, magnetic modeling results and interpretation.

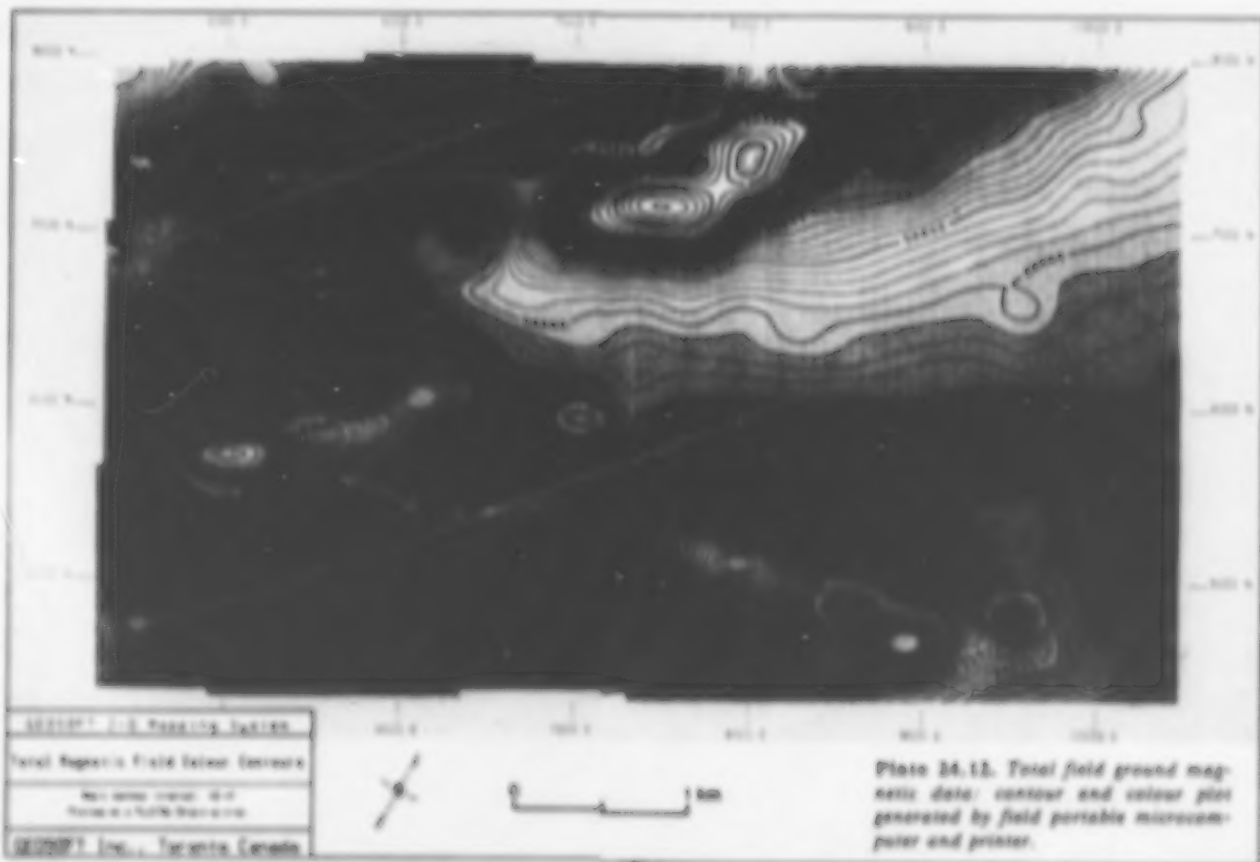


Plate M.11. Total field ground magnetic data: contour and various plots generated by field portable microcomputer and printer.


**CR-AMT APPARENT
RESISTIVITY
LINE 12N**

R.D. RAW AMT



Photo 18.1


**CR-AMT INVERTED
RESISTIVITY
LINE 12N**

R.D. AMT

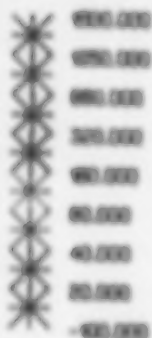


Photo 18.2


**ASSAY RESULTS
LINE 12N**

R.D. (PRL) ASSAY 20



Photo 18.3

Photos 18.1, 18.2, and 18.3. Coloured sections of line 12N for the raw apparent resistivities, the inverted CR-AMT, and the four-percent Zn-Pb. All were processed in a similar fashion

to minimize any effects due to computational bias. The two AMT sections correlate well with the grade section, reinforcing the usefulness of the AMT technique.



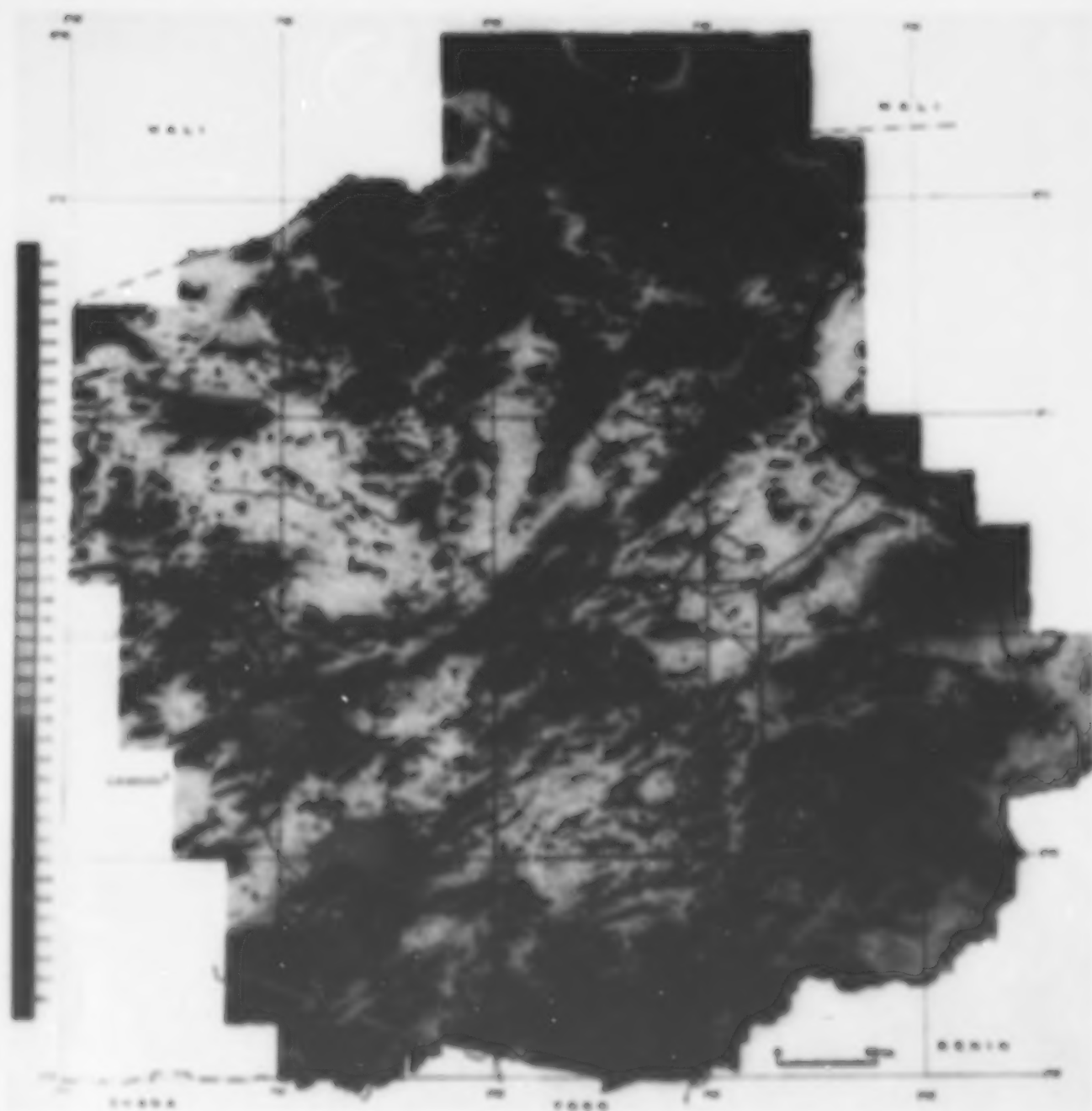


Plate 19.1. Aeromagnetic colour map of the Lipoko-Gourma area of Burkina Faso, Niger and Mali, western Africa; showing Fada N'Gourma Sheet 1.

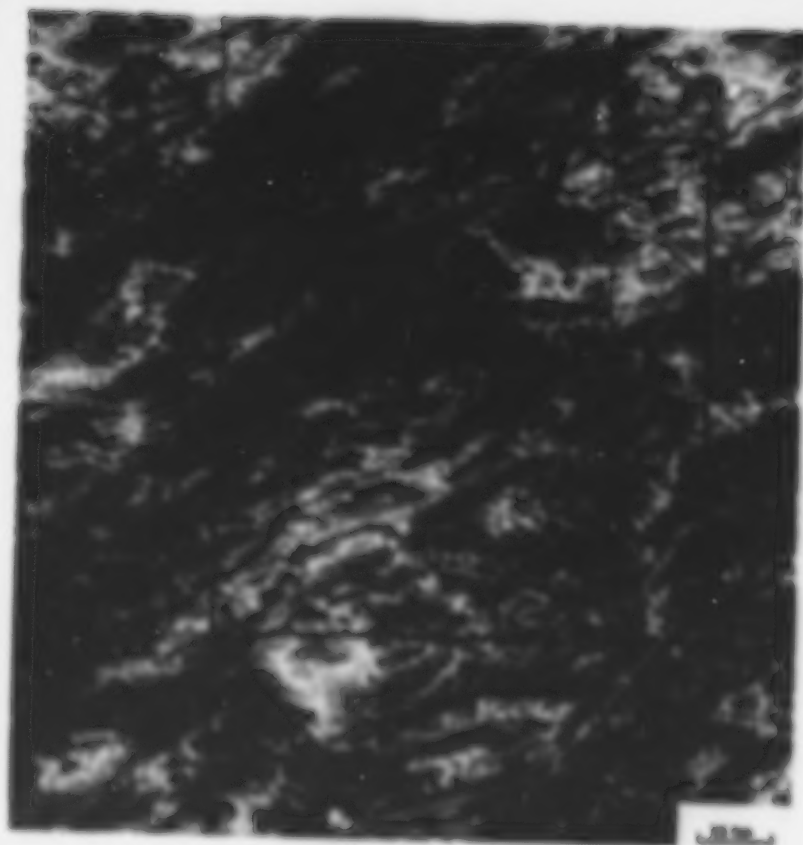


Plate 18.3. Aeromagnetic colour map of the Feds N'Gourma sheet (part of Plate 18.1).



Plate 18.1. Regional Magnetic Survey's total field magnetic for northern Saskatchewan published by the Geological Survey of Canada. The Wollaston Domain is evident as a linear belt of generally low magnetic signature caused by the predominance of Apatite Monzonite. The four study areas are located in the western Wollaston Domain.

0 40 80 120 160 km

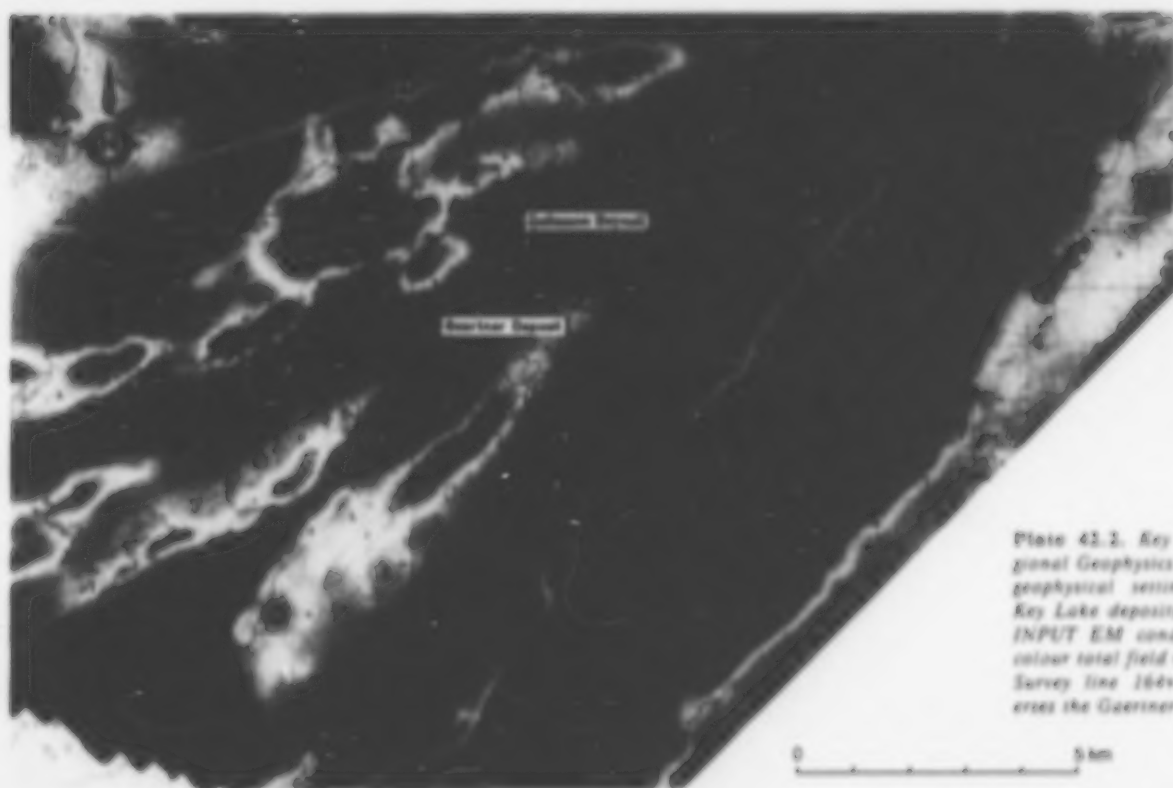


Plate 41.2. Key Lake Regional Geophysics: Regional geophysical setting of the Key Lake deposits, showing INPUT EM conductors on colour total field magnetics. Survey line 184500E traverses the Guerin orebody.

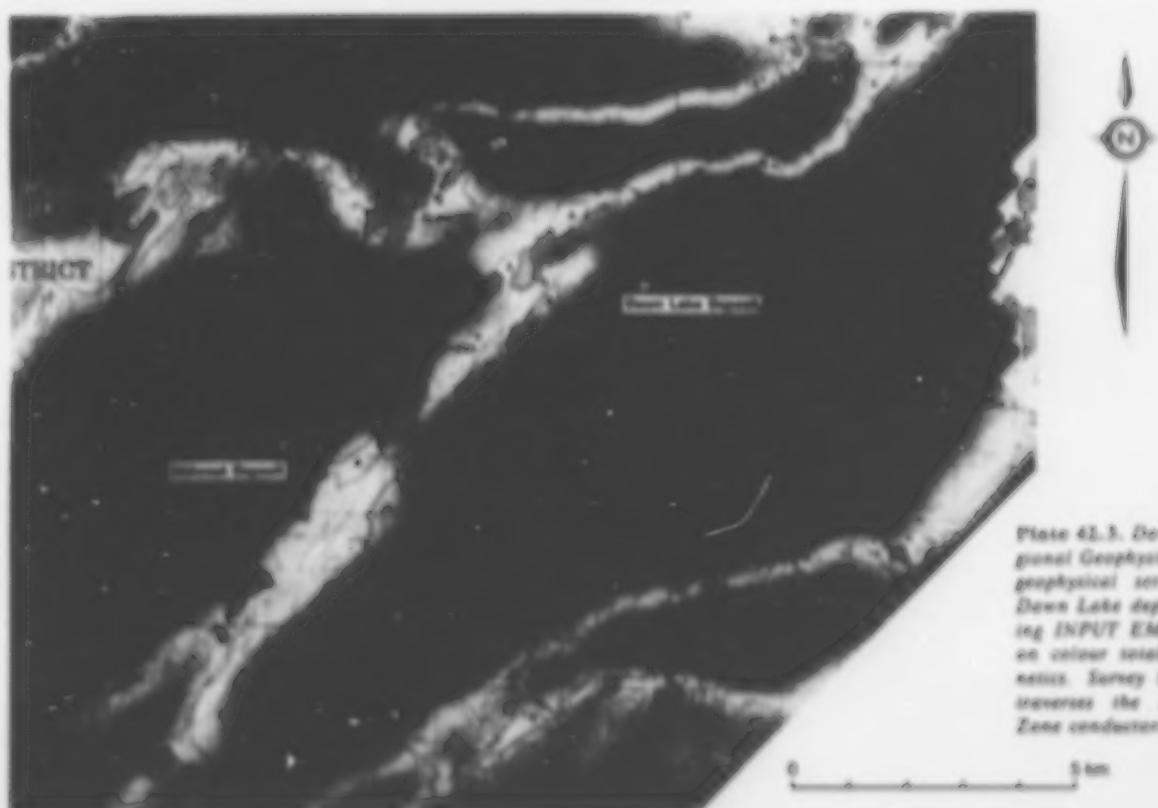


Plate 41.3. Down Lake Regional Geophysics: Regional geophysical setting of the Down Lake deposits, showing INPUT EM conductors on colour total field magnetics. Survey line 51400N traverses the 11 and 14 Zone conductors.

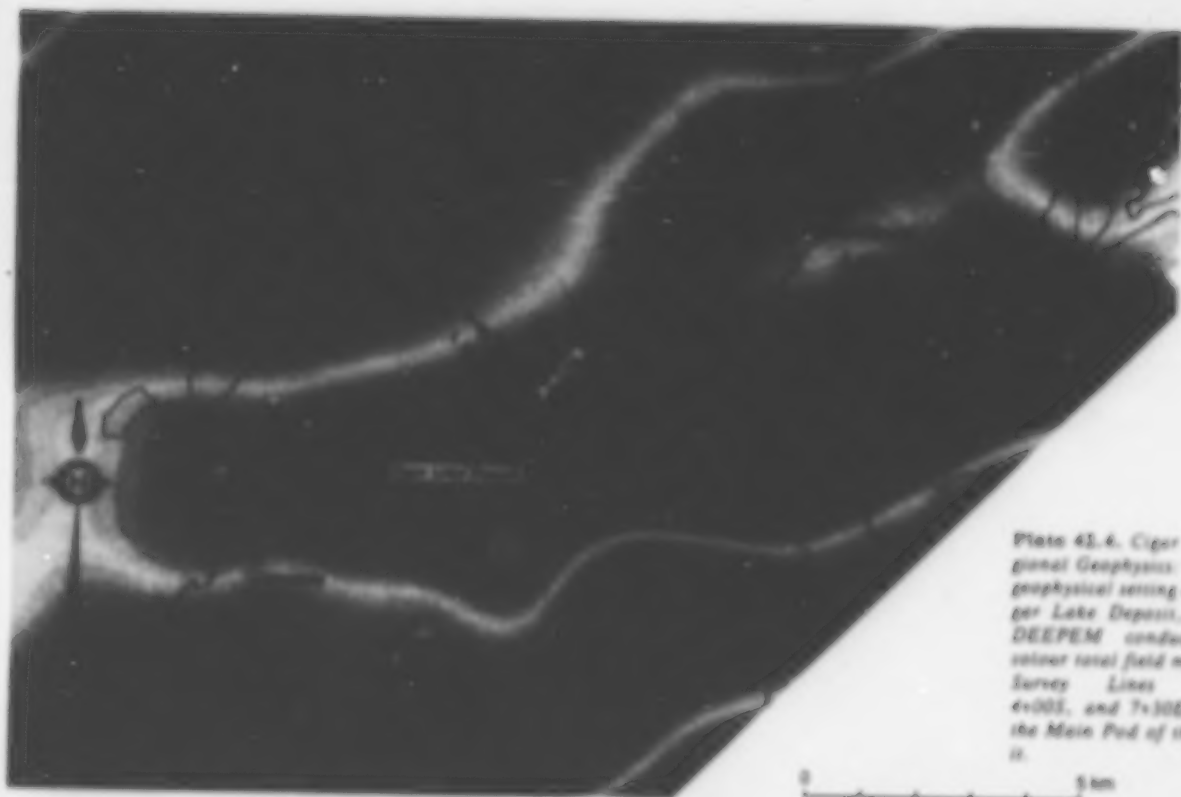


Plate 41.4. Cigar Lake Regional Geophysics: Regional geophysical setting of the Cigar Lake Deposit, showing DEEPEM conductors on colour total field magnetic. Survey Lines 10+001, 4+001, and 7+30E traverse the Main Pod of the deposit.

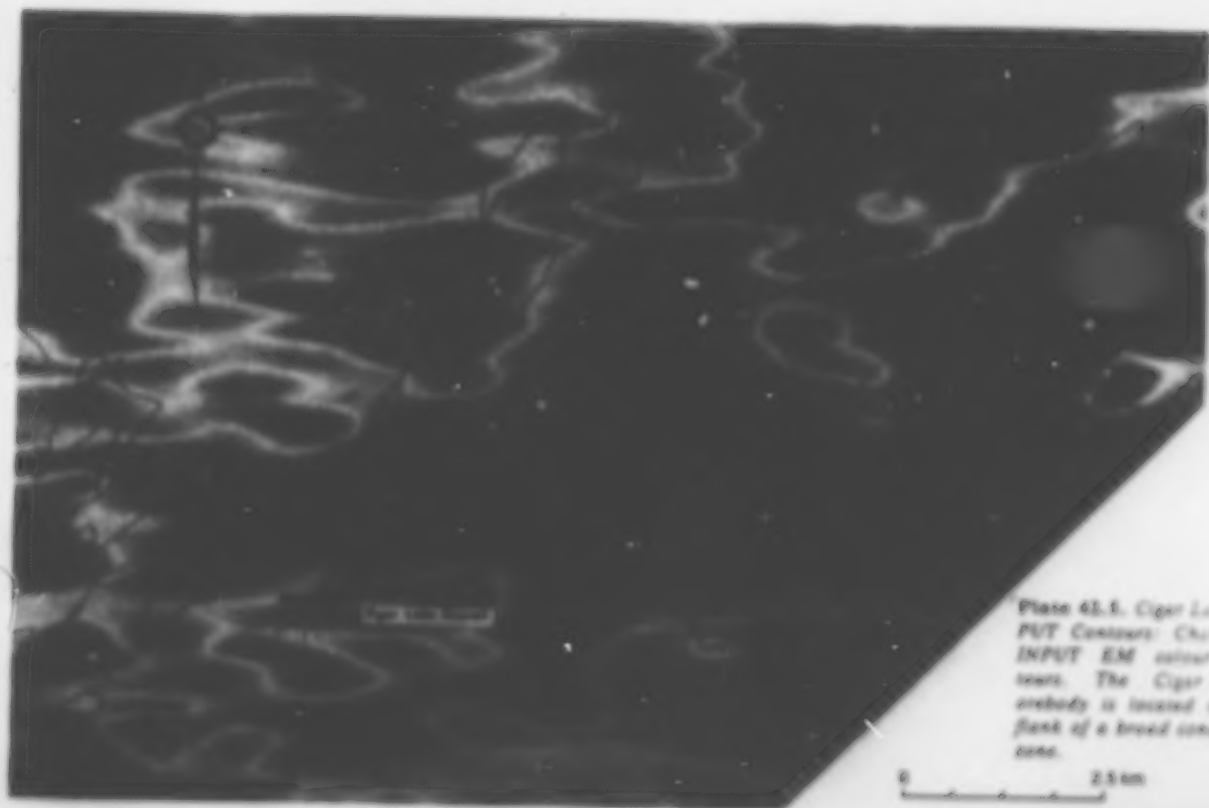


Plate 41.5. Cigar Lake EM PUT Contours: Channel 1 INPUT EM colour contours. The Cigar Lake orebody is located on the flank of a broad conductive zone.

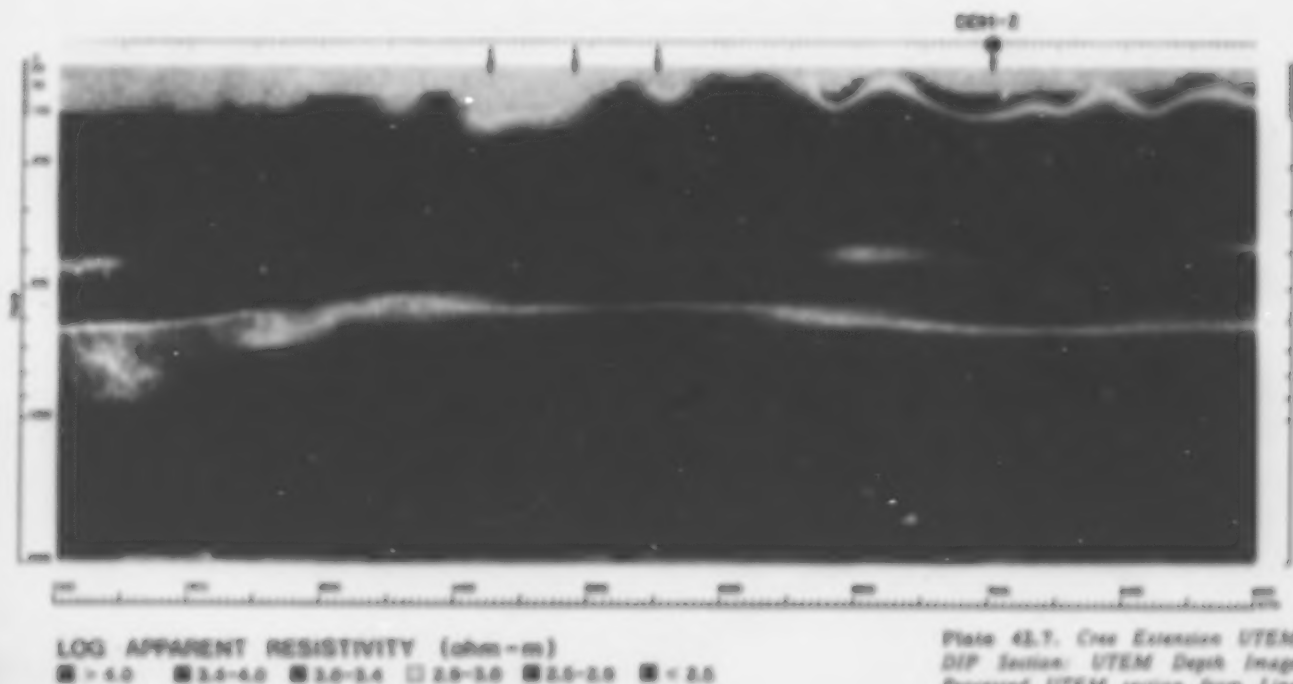
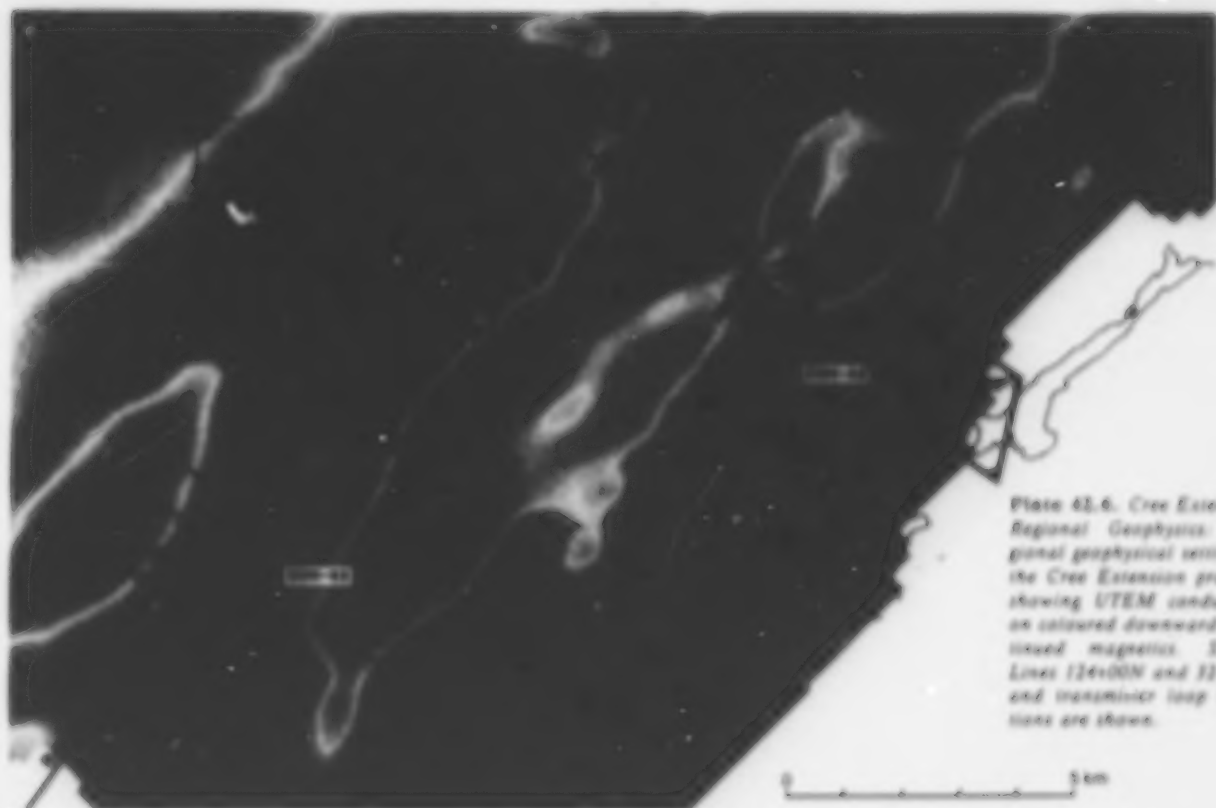




Plate 61.1. Ternary radioclement map of the Cat Lake-Winnipeg River district, southeastern Manitoba (Geological Survey of Canada 1987). Geology after Cerny et al. (1981).

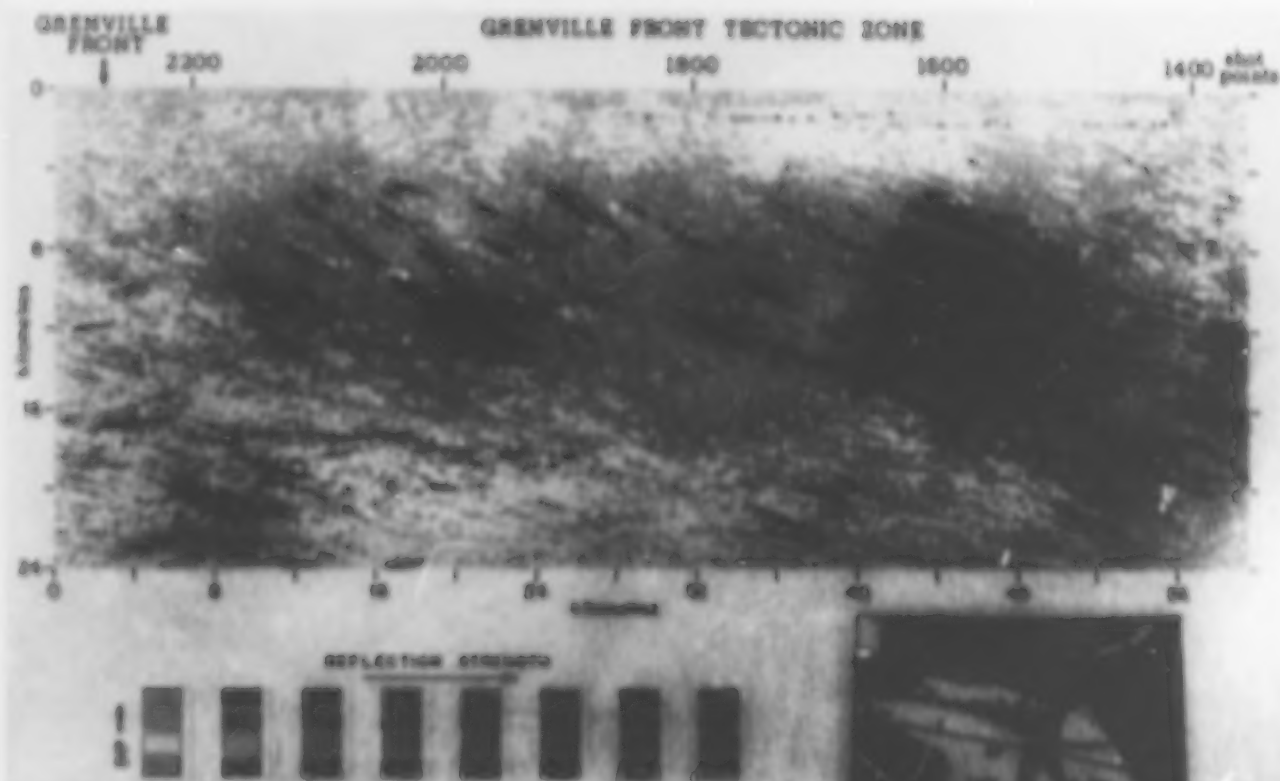


Plate 61.2. Seismic reflection cross-section across Grenville Front tectonic zone (courtesy of A. Green, Geological Survey of Canada).

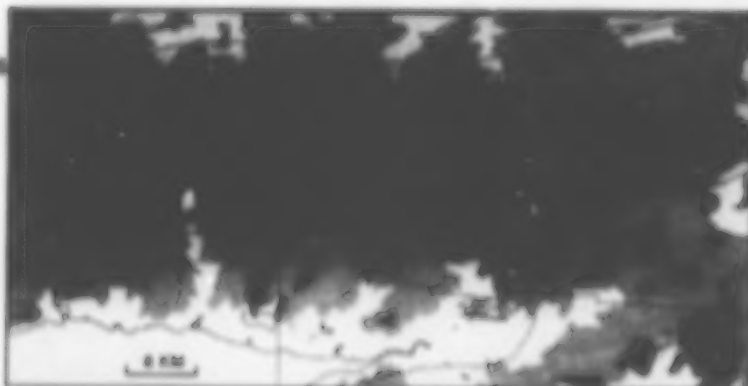
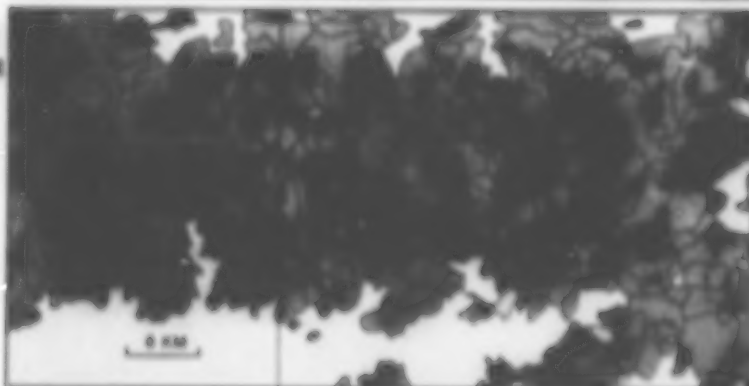
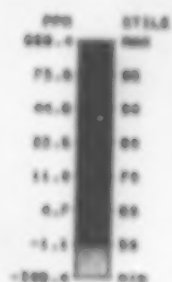
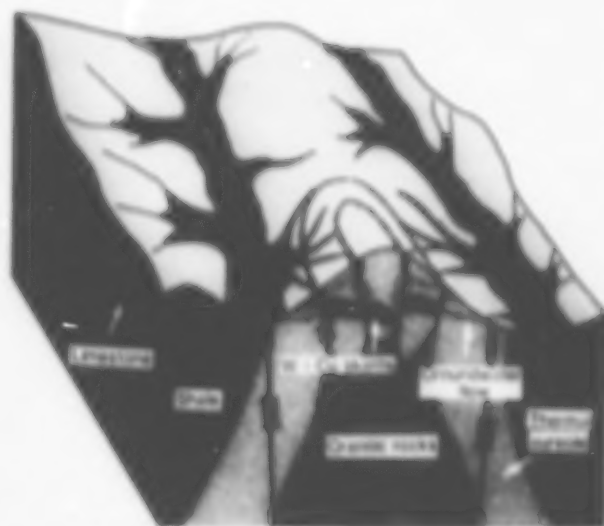
ZINC
IN
STREAM SEDIMENTSZINC RESIDUALS
IN
STREAM SEDIMENTS

Plate 61.3. Distribution of zinc in stream sediment in the Cobequid Highlands of Nova Scotia, using catchment basins upstream from each sample site as a zone of influence: a) digital image of observed data, b) residuals after removal of background predicted from geology (after Bonham-Carter et al. 1987).



Partial Pb, Ag, Sb, As value
Drainage pattern
Fault
Surface projection of ring fractures

Stream Geochemical

Anomalies
W, Cu
As, Pb, Ag, Sb
Acid pH

Plate 61.4. Some elements of a descriptive model for tungsten skarn deposits and the predicted geochemical dispersion

due to circulation of groundwaters through ring fractures (after Aronoff et al. 1988).

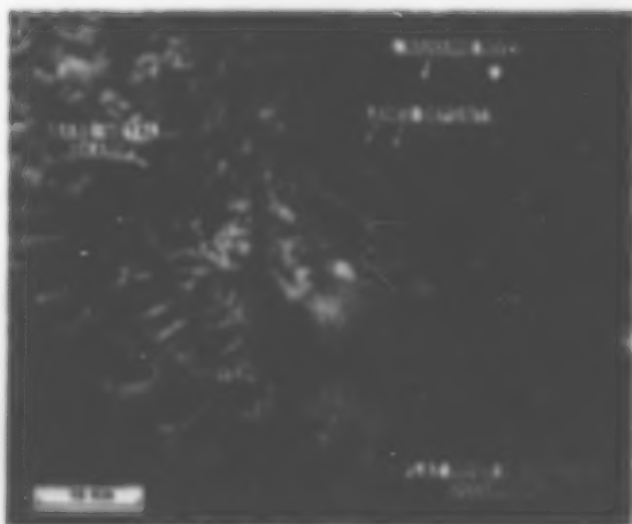


Plate 61.5. Integration of multiple data sets. Superimposed Landsat imagery (with ring fractures highlighted), geological data (plutons in red), mineral occurrences, and stream sediment geochemical data (anomalies in yellow) (after Aronoff et al. 1988).



Plate 13.2. PCA colour composite of low altitude airborne magnetic and electromagnetic (real and imaginary) data, sulphide and PGE orebodies, Norblast area.



Plate 13.1. PCA colour composite of low altitude magnetic and electromagnetic (real and imaginary) data, nickel-copper orebodies, Vammala area.

- ▲ Vammala
Ni-Cu Deposit
- Vammala
Formation



Plate 14.1. Golden Pond long electromagnetic-conductivity data superimposed (from Dawson et al. 1984).

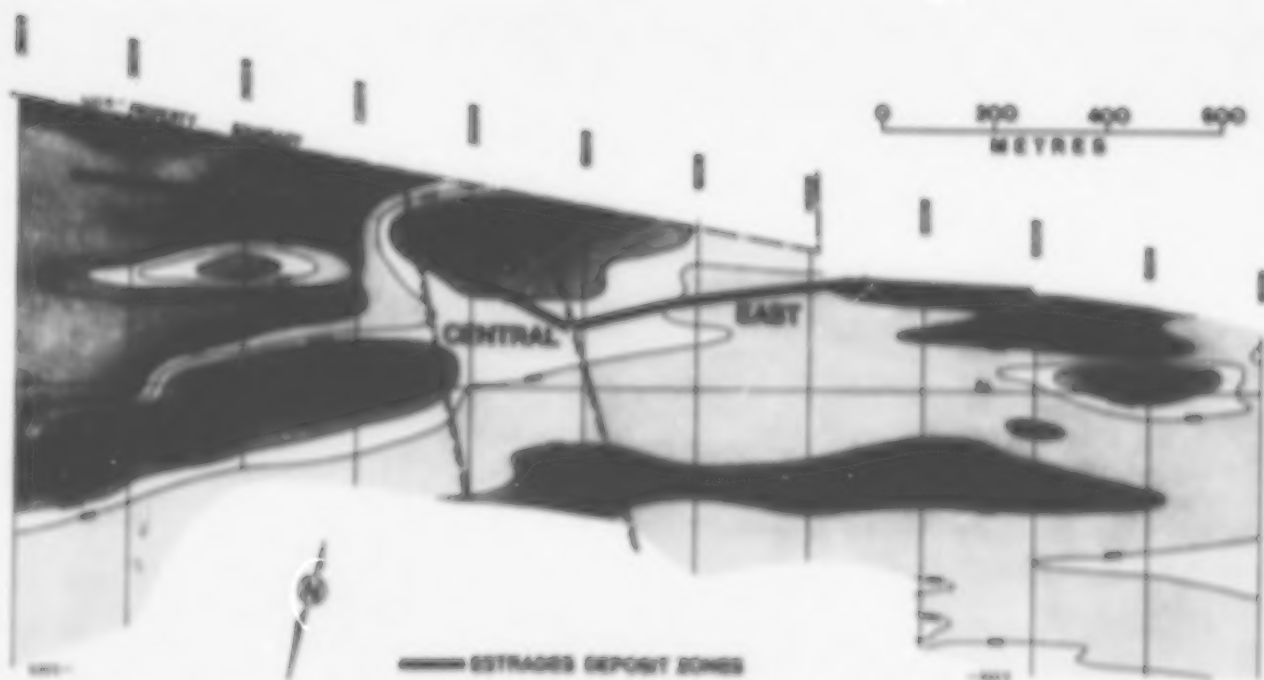


Plate 14.2. Estrada Deposit: Total field magnetic contours and horizontal loop electromagnetic-conductor axes.

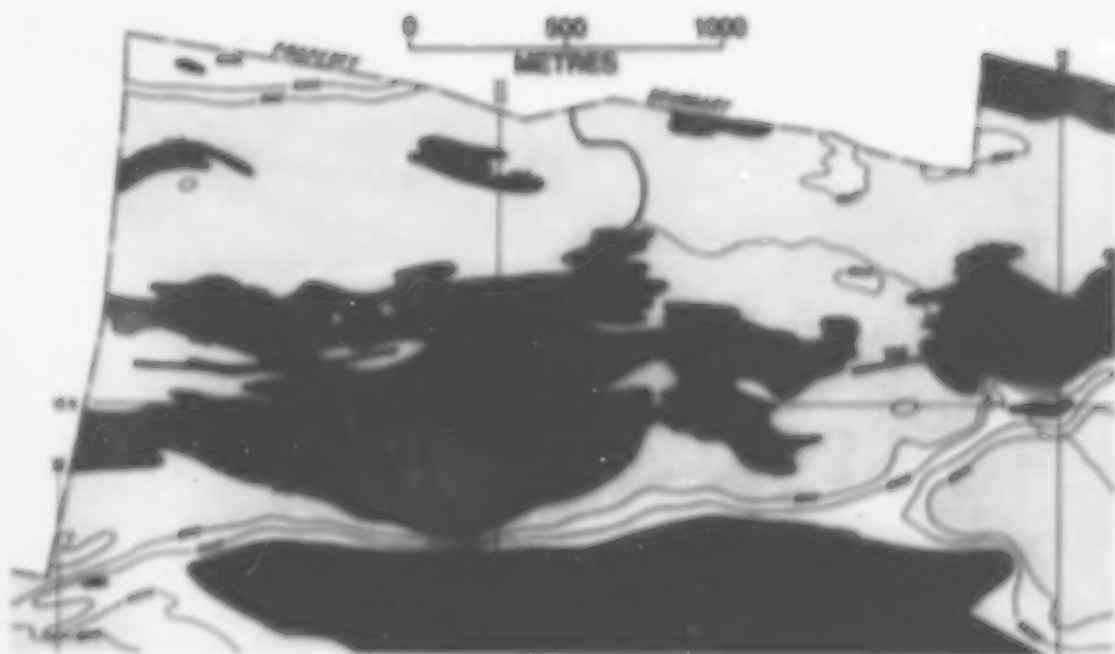


Plate 14.3. Boulder Mountain Trend: Total field magnetic contours with horizontal loop electromagnetic-conductor axes superimposed.

49. State-of-the-Art Geophysical Exploration for Geothermal Resources

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ABSTRACT

Geophysics plays important roles both in the exploration for geothermal systems and in delineating, evaluating and monitoring production from them. The thermal methods, which detect anomalous temperatures directly, and the electrical methods are probably the most useful and widely used in terms of rising drilling targets, but gravity, magnetic, seismic methods, and geophysical well logging all have important application. Advances in geophysical methods are needed to improve cost effectiveness and to enhance solutions of geological problems. There is no wholly satisfactory electrical system from the standpoint of resolution of subsurface resistivity configuration at the required scale, depth of penetration, portability of equipment and survey cost. The resolution of microseismic and microearthquake techniques needs improvement and the reflection seismic technique needs substantial improvement in order to be cost effective in many hard-rock environments. Well-logging tools need to be developed and calibrated for use in corrosive wells at temperatures exceeding 200°C. Well-log interpretation techniques need to be developed for the hard-rock environment. Borehole geophysical techniques and geotomography are just beginning to be applied and show promise with future development.

INTRODUCTION

PURPOSE

In this paper we seek to review the application of geophysical methods to geothermal exploration and development, to assess the current state-of-the-art, and to discuss certain areas of current research and development. Previous reviews of geophysical applications have been given by Ward (1982b), Rapolla and Keller (1984), and Wright *et al.* (1985), among others.

NATURE OF GEOTHERMAL RESOURCES

Geothermal resources have three common components: a) a heat source, b) a reservoir with porosity and permeability, and c) a fluid to transfer the heat to the surface. One useful classification of geothermal resource types is shown in Table 49.1. Hydrothermal resources are those characterized by natural thermal waters, and are divided into those with

TABLE 49.1: GEOTHERMAL RESOURCE CLASSIFICATION (MODIFIED FROM WHITE AND WILLIAMS 1975).

RESOURCE TYPE	TEMPERATURE CHARACTERISTICS
Convective Hydrothermal Resources	
Vapor dominated	~240°C
Hot-water dominated	~30°C to 330°C
Other Hydrothermal Resources	
Sedimentary basins/Regional aquifers (hot fluid in sedimentary rocks)	~30°C to 150°C
Geopressured (hot fluid under pressure that is greater than hydrostatic)	~90°C to 200°C
Radiogenic (heat generated by radioactive decay)	~30°C to 150°C
Hot Rock Resources	
Part still molten	higher than 600°C
Solidified (hot, dry rock)	90° to 450°C

significant large-scale convection and those without. Hot-rock resources have no natural fluid to transport heat to the surface, and are the subject of current research to develop means of extracting their energy. Only the hydrothermal resources have been developed to any extent.

Convective hydrothermal resources are geothermal resources in which the earth's heat is actively carried upward by the circulation of naturally occurring hot water or steam (Figure 49.1). Underlying some of the higher-temperature resources is presumably a body of molten or recently solidified rock whose temperature may be in the range 400°C to 1100°C. Other convective resources result simply from circulation of water along faults and fractures or within permeable aquifers to depths where the rock temperature is elevated, with heating of the water and subsequent buoyant transport to the surface or near surface.

As a matter of convenience, it has been customary to speak of high-temperature resources as those having temperatures above 150°C, of intermediate-temperature resources as those with temperatures in the range 90°C to 150°C, and of low-temperature resources as those with temperatures below 90°C.

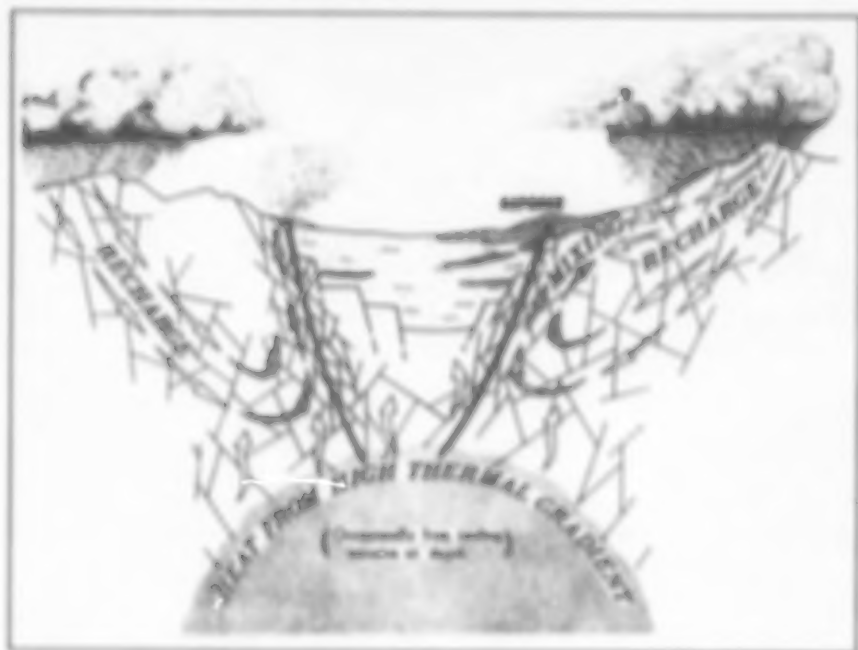


Figure 69.1. Generalized model of convective hydrothermal system (after Ward et al., 1981, reprinted by permission of American Association of Petroleum Geologists).

High-temperature and some moderate-temperature resources are partially amenable to development for electrical power generation, whereas those of lower temperature are usually considered for some direct-heat use such as space conditioning or industrial-processing heat. The preponderant use of geophysics has been in the exploration for and the delineation of moderate- and high-temperature hydrothermal resources. The economics of development of low-temperature resources usually preclude anything beyond a simple, low-cost exploration effort. Because it is only the hydrothermal type that is commercially viable today, we will restrict our discussion to hydrothermal resources.

Several physical and chemical properties of hydrothermal systems lend themselves to geophysical detection and mapping (Table 49.2). Geothermal resources cause enhanced geothermal gradient and heat flow. Hydrothermal resources generally cause the electrical resistivity to be lower than regional values because of the high conductivity of hot brines and because clay minerals, formed as a result of hydrothermal alteration, also enhance the conductivity. In addition, hydrothermal resource areas are often fractured, and the increased permeability enhances electrical conductivity. Local and regional structure as well as changes in density and magnetic properties of rocks associated with geothermal resources are often detectable by gravity and magnetic surveys. Seismic properties of rocks in the vicinity of

hydrothermal resources are sometimes modified, and seismic methods can also be used to detect active hydrothermal processes.

EXPLORATION STRATEGY

Hydrothermal convection of fluids through structures is a phenomenon that occurs in high-, moderate-, and low-temperature environments. Although all systems are basically similar, each has its own unique characteristics. Thus, although a general exploration strategy for hydrothermal systems can be proposed, the strategy will require some modification to fit the demands of most individual exploration projects.

Ward et al. (1981) proposed the formulation of exploration models and the constant updating of these models as exploration proceeds. They state that the most efficient exploration programs are based on a knowledge of the physical or chemical processes within a convection system and an interpretation of the geological, geochemical, geophysical, and hydrological manifestations of these processes. For each increment of exploration dollars, these models should be updated and the important controlling parameters of systems should be documented, analyzed, and understood. A genetic model is the end point of the entire process with the exploration model approaching the genetic model as each new increment of data is received. In short, it is not necessary to understand fully a system to explore it;

TABLE 49.2: GEOTHERMAL TARGETS IN
GEOTHERMAL EXPLORATION (AFTER
WRIGHT ET AL. 1982).

METHODS	TARGETS
HEAT FLOW	Thermally anomalous rocks or fluids
ELECTRICAL	
Resistivity	Hot brines, alteration, faults
Induced Polarization	Alteration, mineralization
CSEM & Sealer AMT	Hot brines, alteration, faults
MT/AMT	Hot brines, magma chamber, partial melt, structure
Self Potential	Flow of fluid and heat
Tellurics	Hot brines, alteration, faults
GRAVITY	Structure, alteration, densification, intrusions
MAGNETICS	Structure, alteration, rock type
SEISMIC	
Microseismic	Active hydrothermal processes
Microearthquakes	Active faulting & fracturing, distribution of velocity & attenuation
Teleseisms	Deep magma chamber
Reflection	Structure distribution of velocity and attenuation
Refraction	Structure distribution of velocity and attenuation
RADIOMETRIC	Alteration, ^{40}K index, ^{87}Rb index
WELL LOGGING	Anomalous temperature, porosity, permeability, rock type
WELL LOGGING	
VSP	Velocity distribution, fractures
Electrical	Hot brines, alteration, faults

It is sufficient to understand the fundamental processes of a system and to understand its detection by various exploration tools.

Figure 49.2 portrays a basin strategy for exploring for high-temperature hydrothermal resources in the Basin and Range Province, of the southwestern U.S.A., in areas of surface thermal manifestations. As recommended by Ward et al. (1981) and as noted earlier, modifications to this strategy assume that one starts with a nominal district of 1000 km² and finds one high-priority prospect in this area which eventually demands a production test. If other prospects are found in the district, they would be considered of lower priority than one drilled for production. The strategy recommended is a minimum one, yet its cost through drilling and logging and subsequent reservoir modeling is estimated to be \$4.6 million (1981 U.S. dollars) if both seismic reflection and magnetotelluric surveys are included.

Where do these costs arise? Each box in the flow diagram of Figure 49.2 depicts a function or functions whose cost estimate is shown to the right of the box. The sequence of events in the flow diagram has been carefully considered to provide the most cost-effective data gathering consistent with the risk involved. By design, the risk of failure should become less as one moves downward in the diagram, that is, forward in time, so that higher cost or less demonstrated, yet promising, exploration techniques can be justified late but not early. Ward et al. (1981) present a detailed justification for this strategy.

STATE-OF-THE-ART

In this section we give a brief discussion of the methods and an evaluation of the state-of-the-art in application of geophysics to exploration for and within mid- and high-temperature geothermal systems.

THERMAL METHODS

Several thermal methods respond to high rock or fluid temperature, and provide the most direct indication of a subsurface geothermal resource. Thermal gradient and heat-flow surveys are usually a component of the exploration program (Ward et al. 1978; Smith 1984). Drillholes must be deep enough to penetrate the near-surface hydrological regime, which may be dominated by vertical and lateral flow of cold water. In some areas, shallow temperature surveys are made in holes 2 to 5 m deep for the purpose of detecting anomalous subsurface temperatures (Lefschick and Lewis 1983). Snow-melt photography and thermal-infrared imagery have also been used to detect potential geothermal resource areas (White 1969; Dickinson 1976).

Instrumentation for the precise measurement of temperatures downhole is adequate for temperatures below approximately 250°C, but above this temperature several components of usual borehole systems begin to fail in the corrosive hydrothermal environment. Logging equipment rated for higher temperatures is needed for study of the high-temperature parts of hydrothermal systems as well as for hot-rock environments such as those that will be encountered in deep, continental, scientific drilling. Instrumentation for measuring thermal conductivity is adequate. A better understanding of the variations of this parameter with temperature, pressure, porosity, and hydrothermal alteration is needed, however.

A particularly important topic for geothermal exploration is the relationship between measured thermal gradient and heat flow and the local and regional hydrological regime. Smith and Chopman (1983) give a review of previous work made on this topic and report numerical solutions for the equations of fluid flow and heat transport used to quantify the effects of groundwater movement on the



Figure 6.1. Integrated light components hydrothermal spring. Numbers at left of blocks indicate opening sequence. Σ numbers at right of blocks indicate summed Σ . Dollar sign is thousands (after Ward et al., 1981, reprinted by permission of American Association of Petroleum Geologists).

subsurface thermal regime. In parallel, there is a significant effort by the reservoir engineering community to understand the mechanisms and effects of heat and mass transfer within hydrothermal systems (e.g., see Bodvarsson 1982). A great deal more work remains to be done at this interface between geophysics and hydrology. Continued development of two- and three-dimensional algorithms to model jointly the hydrology and heat transport in complex geological situations, including uplift, deposition, erosion, faulting, extension, and intrusion, is needed.

Available equipment and interpretation techniques for shallow-depth temperature surveys are adequate, and experience reported in the literature is sufficient to facilitate decisions on whether or not to apply this technique in specific exploration problems. The thermal-infrared technique has seen only limited use in hydrothermal exploration, and this will continue to be the case as exploration emphasizes more and more the search for concealed resources.

ELECTRICAL METHODS

Perhaps the most important physical property changes due to the presence of a hydrothermal system, other than elevated temperatures, are the changes in the electrical properties of the rock-fluid volume. Higher temperatures increase ionic mobility up to about 100°C, and hence increase conductivity. Ionic conduction in rocks also increases with increasing porosity, salinity of the fluids, and increasing amounts of certain minerals such as clays and zeolites. Most hydrothermal systems have an associated zone of anomalously low resistivity due to one or more of these factors. The electrical methods map the structures or units controlling present-day permeability of hydrothermal systems as well as past positions of the hydrothermal centre.

At depths exceeding 1 to 15 km, mineral semi-conduction dominates aqueous electrolytic conduction, and partial oxide and magnetite may become highly conductive (Lahetuo and Elitarso 1964). The magnetotelluric (MT) method has been used in an attempt to detect magma beneath several known hydrothermal systems and calderas, but no successful application has been reported (Newman et al. 1981; Sorey et al. 1987).

There is no wholly satisfactory electrical method for exploration for concealed resources in rugged volcanic terrain. Galvanic resistivity surveys, while relatively easy to run and for which interpretation methods are reasonably well worked out (Kilpatrick and Hahmann 1979), often lack adequate depth penetration. Scalar audiomagnetotelluric (AMT) surveying does not provide enough data to resolve the subsurface resistivity structure adequately. The tensor MT/AMT method is able to resolve complex structure better, but uses sophisticated, marginally portable equipment requiring a highly trained crew

and also requires complex, sophisticated three-dimensional interpretation. The controlled-source electromagnetic (CSEM) methods are relatively easy to run but equipment is only marginally portable and adequate two- and three-dimensional interpretation is only now becoming feasible (Ward 1981a). Self-potential (SP) surveys are easy and inexpensive but quantitative interpretation is difficult and usually ambiguous in terms of the geological causes of the anomalies. Substantial gains in quantitative interpretation theory have recently been made (Sill 1983), but the algorithms are probably in limited use. We consider the rather current method to have only limited application because of its semiquantitative nature. In view of the relevance of electrical methods to geothermal exploration, further development of electrical equipment and techniques specifically for the geothermal environment would seem like a wise research investment.

GRAVITY AND MAGNETIC METHODS

The gravity method is used to map intrusions, faulting, deep valley fill and geological structure in general. Geothermally related anomalies in sedimentary rocks are commonly residual highs that are believed to reflect denaturation of porous sediments through hydrothermal mineral deposition and metamorphism (Buckler 1971; Muller and White 1969). Magnetic surveys are used for structural and tectonic mapping and for detecting decreased magnetization of rocks due to hydrothermal alteration (Stoll 1964). Magnetic data can also be used to determine the depth to the Curie isotherm (Bhattacharyya and Lee 1975; Okubo et al. 1983), but these interpretations are dependent on many assumptions and therefore have limitations (Shurey et al. 1977).

The gravity and magnetic methods seem to be developed adequately for routine application to geothermal exploration problems. Advances in instrumentation and interpretation will continue to be made and will be adapted as appropriate for geothermal use. One promising application of microgravity surveys is in the long-term monitoring of the effects of production from hydrothermal reservoirs (Crannell 1980).

SEISMIC METHODS

The various seismic methods have found use in geothermal exploration and assessment, and show a great deal of promise. Microseismic surveys have been conducted for the purpose of detecting seismic radiation resulting from hydrothermal processes (Dyer and Hinchinck 1976). Limited success has been reported in some areas by Law and McEvilly (1979), Oppenheimer and Iyer (1980), and Law and Suyemaga (1982). Microearthquake studies have been carried out for the purpose of detecting the active faulting that is postulated to occur in hydrothermal areas in order to maintain permeability in the face of chemical deposition and hydrothermal

absorption in the pores and fractures (Hunt and Latham 1982). Measurement of either the absorption coefficient or a differential attenuation number called ^{-}Q may reveal the presence of exceptionally lossy materials in a reservoir due to fluid-filled fractures, or it may reveal the presence of low-loss materials due to steam-filled fractures or to silica- or carbonate-filled fractures. Major and McEvilly (1979) found a high value of Q in the steam production zone at The Geysers, California from microearthquake and refraction surveys, whereas they found a lower Q value deeper in the crust from a refraction survey.

Teleseisms have been used to measure velocities beneath geothermal areas. A magma chamber would be expected to give rise to low P -wave velocities and an S -wave shadow. Iyer *et al.* (1979) found P -wave delays as large as 0.9 s at The Geysers and Robinson and Iyer (1981) reported relative P -wave delays of up to 0.3 s at Roosevelt Hot Springs, Utah. In recent years, the level of sophistication in applying P -wave velocity studies to the study of volcanoes and other geothermal areas has increased substantially (Weaver *et al.* 1982; Stauder *et al.* 1982).

The seismic refraction and reflection methods have been used to map stratigraphy and structure in some geothermal areas, but the complex geology in many areas appears to present very difficult problems using today's techniques. Conventional refraction surveys give good definition of both the Basin and Range's border faulting and depths of alluvial valley fill, but show little obvious lithological or structural information within the ranges or within known hydrothermal reservoirs (Ross *et al.* 1982). At Beowawe, Nevada, extensive and varied digital processing was ineffective in eliminating the ringing due to a complex near-surface intercalated volcanic-sedimentary section (Swilk 1979).

The microseismic methods lack adequate field testing, largely because of the poor level of understanding of survey design and data analysis prior to about five years ago. Continued work on data processing and interpretation as well as further testing in geothermal environments appear to be warranted. Microearthquake surveys have potential to contribute to defining drill targets especially for deep or blind hydrothermal systems. Low-expensive equipment is needed so that field-deployment time can be increased to mitigate to some extent the episodic nature of the phenomenon. Equipment, interpretation and field testing of the teleseismic and refraction techniques are deemed to be adequate for routine application where appropriate, although we recognize that advances will continue to be made.

The seismic reflection method has potential for greater contributions to geothermal work than it has made to date. The method will always be expensive per unit of coverage, but if the information derived could be increased, an adequate payoff may result.

Portable, high-resolution gear is just now becoming available for shallow reflection work in the hard-rock environment. Better techniques of data acquisition and processing are needed for use in volcanic terrain, many of which are considered bad recording areas even after years of research by the petroleum industry.

RADIOACTIVE METHODS

Auriferous gamma-ray surveys have found little application in geothermal exploration. The use of alpha-ray detectors for radon emanating from hydrothermal systems has been reported by Wollensberg (1974). Surface radon emission surveys appear to be capable of detecting open channels that may conduct geothermal fluids; nevertheless, very little use has been made of the method in geothermal exploration. It is unlikely that conventional radioactive methods will ever play a significant role in geothermal exploration.

WELL LOGGING

There are significant needs for both new equipment development and for new interpretation techniques in well logging, and these needs have been summarized in Sarreal *et al.* (1980) and by Lawrence Berkeley Laboratory (1984). The main instrumentation problem is lack of downhole tools for logging in slim holes at geothermal temperatures. Most tools are limited to temperatures below 175°C to 200°C, although a few have capability to 240°C. Neither tools nor cable exist for temperatures above 200°C. This lack of high-temperature downhole instrumentation seriously compromises the quantity of data that can be obtained in many of the hydrothermal systems currently under production or development. Regarding interpretation, few of the available tools are calibrated for the hard-rock environment, and quantitative interpretation techniques remain to be worked out for many of the measurements. In summary, relatively little of the well-logging sophistication available in the petroleum industry is available to the high-temperature geothermal industry.

BORHOLE GEOPHYSICS

As a general statement, borehole geophysics has not undergone the development required even to assess its potential contribution to geothermal development. The vertical seismic profiling (VSP) techniques have emerged as being important in petroleum exploration (Christaghi 1981), and development for these purposes will have an important spin-off for geothermal applications. Electrical borehole techniques have been neither developed nor seriously applied, although some numerical modeling capability exists to assess their contribution. Seismic geonavigraphy is in the research and development stage, and in analog, electrical geonavigraphy, has received virtually no effort. We believe that the borehole techniques are fertile ground for research and development.

FUTURE DEVELOPMENTS

Table 49.1 summarizes our assessment of the state of the art for each of the geophysical techniques and gives an assessment of the needs in the categories "instrumentation", "interpretation", and "experience". By the latter category, we mean experience in field application of the method used over known geothermal resource areas where enough subsurface information is available to evaluate the performance of the method. We believe that development of joint heat flow-hydrological models will continue and will make thermal studies more useful in the future. Electrical methods will continue to contribute to hydrothermal exploration, and improvements will be made in the application of CSEM, tensor AMT, MT, and self-potential methods. Application of seismic methods will improve, especially in the area of

sophisticated, joint interpretation of several sets of complementary seismic data (reflection, refraction, and P-wave delay, for example). Well-logging techniques provide fertile ground for improvement. Now, higher-temperature tools will be developed and interpretation methods will be forthcoming for the high-temperature, hard-rock environments. The borehole methods will be significantly developed during the coming decade, and will enable geoscientists to begin to measure and understand the nature of the permeability that controls hydrothermal systems.

Both seismic and electrical borehole techniques for geothermal application are undergoing development. Meyer *et al.* (1988) report work for the purpose of detecting fractures using P- and S-wave VSP at The Geysers geothermal field in California. Vibrators were used to create both P- and S- waves,

TABLE 49.1. RESEARCH AND TECHNIQUE DEVELOPMENT NEEDS IN GEOPHYSICAL METHODS (AFTER WRIGHT ET AL., 1986).

METHOD	INSTRUMENTATION	INTERPRETATION	EXPERIENCE
Thermal Methods			
Heat Flow-Gradient	Need temp logging to $T < 150^{\circ}\text{C}$	Need models for hydrologic effects, heat transport in hydrothermal environment	Adequate
Shallow Temperature	Adequate	Adequate	Adequate
Thermal IR	Adequate	Adequate	Adequate
Electrical Methods			
Resistivity-IP	Adequate	Need broader use of 2-D, 3-D techniques	Adequate
CSEM	Need portable equipment, reduced costs	Need to develop 2-D, 3-D interpretation techniques	Need better evaluation
Tensor AMT	Adequate	Adequate	Adequate
Tensor MT-AMT	Need portable equipment, reduced costs	Need broader use of 2-D, 3-D techniques available	Need better evaluation
IP	Adequate	Need better interpretation techniques	Need better evaluation
Telluric Current	Adequate	Adequate	Adequate
Gravity Method	Adequate	Adequate	Adequate
Magnetic Method	Adequate	Adequate	Adequate
Seismic Methods			
Microseismic	Adequate	Need further development of techniques	Need better evaluation
Minimarthquake	Need reduced equipment/survey costs		Need better evaluation
Teleseismic	Adequate	Adequate	Adequate
Reflection	Adequate	Adequate	Adequate
Refraction	Need portable high resolution equipment	Need continued development and application of previous technology at reduced costs	Need better evaluation
Radioactive Method	Adequate	Adequate	Adequate
Well Logging	Need temp logging to $T < 150^{\circ}\text{C}$	Need interpretation in hard rock environments	Need better evaluation
Borehole Geophysics			
VSP	Adequate	Adequate	Need evaluation
Electrical	Need equipment	Need to develop techniques	Need evaluation
Geolography	Need equipment	Need to develop techniques	Need experience

with the S-wave vibrator being oriented sequentially in directions parallel to and normal to the dominant fracture set inferred from surface geology and drillhole information. A three-component clamped geophone was used in a shut-in, steam-filled marginal producer, and recording positions were established at 30.5 m intervals between 305 and 1555 m. An incomplete data set was recorded due to failure of the geophone, which was designed for water immersion and which leaked in the steam environment. Such equipment failures are common in working in geothermal wells. However, enough data were collected to indicate that the method has potential for helping to characterize the dominant fractures in the area. Anisotropy of shear waves was evident in an eleven percent velocity difference and in apparent splitting of SH- and SV-polarized waves generated at a common source point and recorded by a common downhole geophone. There was little evidence of P-wave anisotropy. The S-wave anisotropy is consistent to first order with expected effects of the known dominant fracture set in the greenstone caprock overlying the dry steam-production zone. In addition, there was evidence for a decreasing Poisson's ratio as the production zone was approached. This has been interpreted by others as well as by Majer *et al.* 1988) in terms of an increasing fraction of dry steam in the pore space of the rocks. In view of the critical importance of locating fractures in both geothermal exploration and reservoir engineering, the VSP techniques appear to warrant continued research and development.

To provide some insight into progress that is being made in the electrical borehole techniques, the remainder of this paper presents some of the work presently underway in which the authors are involved.

STUDIES IN BOREHOLE ELECTRICAL GEOPHYSICS AT THE UNIVERSITY OF UTAH RESEARCH INSTITUTE

SUMMARY OF PAST STUDIES

It is important to understand the differences between geophysical well logging and borehole geophysics. In geophysical well logging, the instruments are deployed in a single well in a tool or sonde, and the depth of investigation is usually limited to the first few metres from the wellbore.

By contrast, borehole geophysics refers to those geophysical techniques where energy sources and sensors are deployed a) at wide spacing in a single borehole, b) partly in one borehole and partly on the surface, or c) partly in one borehole and partly in a second borehole. Thus, we speak of borehole-to-surface, surface-to-borehole and cross-borehole surveys. The range of investigation is generally much

greater in borehole geophysical surveys than it is in geophysical well logging.

The objective of our program is to develop and demonstrate the use of borehole electrical techniques in geothermal exploration, reservoir delineation, and reservoir exploitation. Our approach is to accomplish the following:

1. develop computer techniques to model the possible borehole electrical survey systems
2. design and construct a field data acquisition system based on the results of (1)
3. acquire field data at sites where the nature and extent of permeability are known
4. develop techniques to interpret field data

To the present time, we have largely completed item (1), made a preliminary design for a multiarray borehole resistivity system (Green and Ward 1986) and acquired field data at one site using the multiarray concept. Our computer modeling is as follows:

1. cross-borehole resistivity (Yang and Ward 1985; Zhao *et al.* 1986)
2. mise-à-la-masse (Beasley and Ward 1986)
3. transient electromagnetic (TEM) (West 1986)
4. controlled-source audiomagnetotellurics (West and Ward 1988)
5. magnetometric resistivity (LaBrecque and Ward 1987)
6. the effect of casing (LaBrecque and Ward, in preparation)
7. Surface-integral equation, volume-integral equation and finite-element methods have been used.

Typical results from our modeling studies are shown in Figures 49.3, 49.4, and 49.5. Figure 49.3, pertaining to TEM, shows contours of apparent resistivity normalized by the resistivity of a homogeneous half-space for a horizontal 1000 by 1000 by 100 m prism of 10 ohm-metres resistivity. The details of the geometry of the transmitting loop, the body, and the borehole are shown in the figure. The prism is clearly detected within the time window 4 to 24 ms.

Figure 49.4, pertaining to the controlled-source audiomagnetotelluric (CSAMT) method, shows profiles of E_z/H_x° where E_z is measured at 100 Hz over a 100 m dipole downhole and where H_x° is measured at surface in a direction parallel to the strike of the body. The real and imaginary amplitudes are plotted to different scales. The prism is 1000 by 1000 by 100 m and is of resistivity 10 ohm-metres in a background which is either 300 ohm-metres or 1000 ohm-metres. Clear-cut anomalies are obtained from which the top and bottom of the body can readily be deduced. As expected, the amplitude of the real component decreases with decreasing host resistivity due to increased attenuation of the

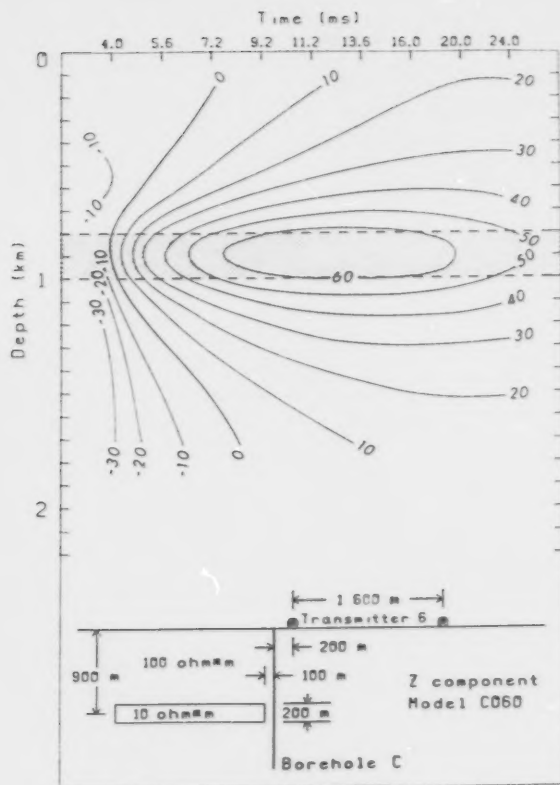


Figure 49.3. Percent-difference (PD) contour plot of the TDEM borehole response for a 10 ohm-metres target at a depth of 900 m in a 100 ohm-metres half-space for an off-side transmitting loop. The contour interval is 10 percent, the time scale is nonlinear, and the depth extent of the target is shaded.

$$PD = \frac{TOTAL - PRIMARY}{PRIMARY} \times 100\%$$

PRIMARY = HALF-SPACE RESPONSE

primary wave. On the other hand, the amplitude of the imaginary component increases with decreasing host resistivity due to a phase shift of the primary wave.

Figure 49.5, pertaining to magnetometric resistivity (MMR), displays the H_x , H_y , and H_z anomalies, in plan view, measured at the surface of the earth over a prism of dimensions 2000 by 1000 by 100 m. The resistivity of the prism is 10 ohm-metres while that of the host is 100 ohm-metres. The downhole electrode is shown by the asterisk in Figure 49.5; the return current electrode is at the surface 1000 m vertically above the subsurface electrode. Hence the source is a vertical electric bipole which yields no primary magnetic field at the surface. Note the quadrupolar, monopolar, and dipolar anomaly patterns for H_x , H_y , and H_z , respectively. One can deduce from these patterns that an electric

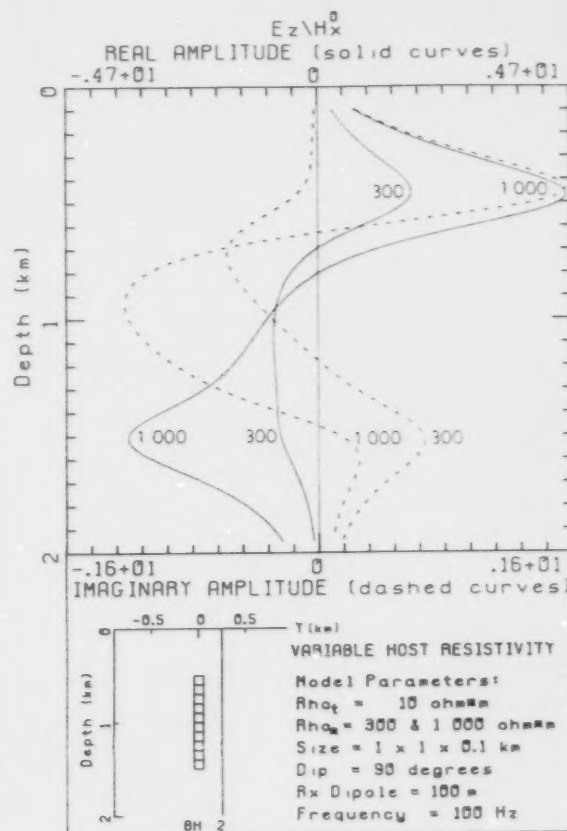


Figure 49.4. E_z/H_x^0 borehole profiles for borehole near a vertical conductive prism embedded within a half-space of resistivity of 300 and 1000 ohm-metres. Resistivity values in ohm-metres are noted and all parameters are specified in the figure (after West and Ward 1988).

bipole is induced in the body. The anomaly values are in nT/A. A substantial current source (10 A) would be required to ensure an adequate ratio of anomaly to natural-field noise.

MULTIARRAY BOREHOLE RESISTIVITY AND INDUCED POLARIZATION METHOD

Description

The multiarray borehole resistivity and induced polarization method (Figure 49.6) relates to a means of converting a conventional long-lateral array used in well logging (current electrodes A_B and B) to a multiarray method capable of providing hole-to-surface ($A_B B M_S N_S$), and surface-to-borehole ($A_S B M_B N_S$) measurements. Rapid sequencing of electrode combinations is necessary so that all measurements are made before the logging sonde has moved significantly up the borehole.

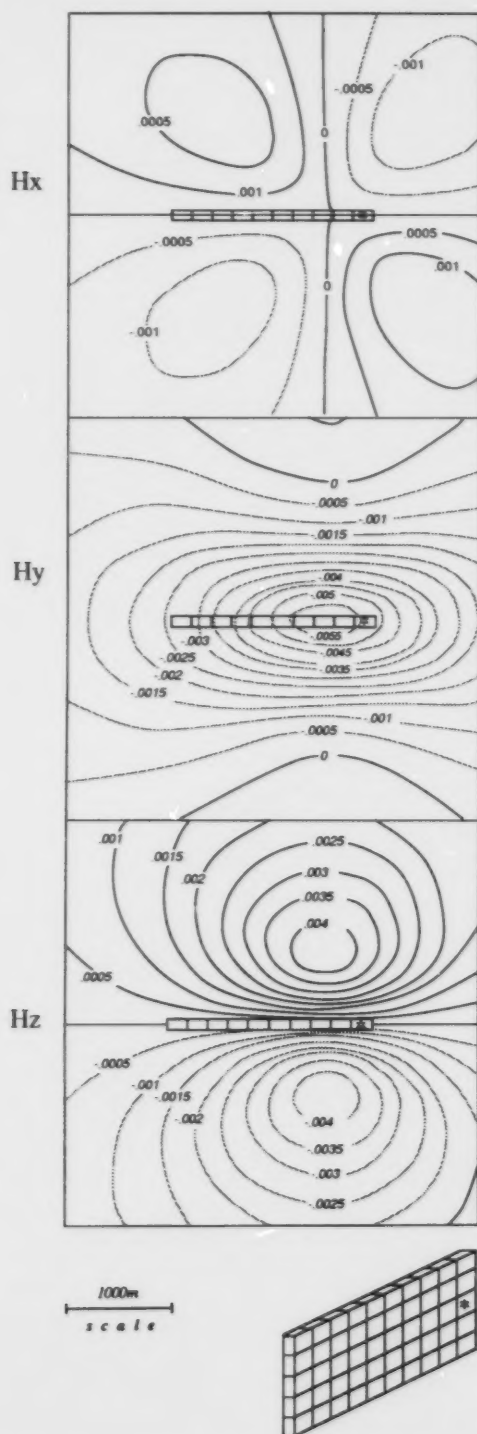


Figure 49.5. Magnetic fields over a vertical prism with strike length of 2000 m. The positive current electrode is located at a depth of 1000 m, 800 m in the x (strike direction) from the centre of the dike and 0 m in the y direction from the centre of the dike. Contours are in nT/A. (after LaBrecque and Ward 1987).

The following sequence of measurements is envisioned:

- | | |
|------------------------------|---------------------|
| 1. B $A_B M_B N_B$ | long lateral |
| 2. B $A_B M_S(-4) N_S(3-)$ | borehole-to-surface |
| 3. B $A_B M_S(-3) (N_S)(-2)$ | borehole-to-surface |
| 4. B $A_B M_S(-2) N_S(-1)$ | borehole-to-surface |
| 5. B $A_B M_S(-1) N_S(0)$ | borehole-to-surface |
| 6. B $A_B M_S(0) N_S(1)$ | borehole-to-surface |
| 7. B $A_B M_S(1) N_S(2)$ | borehole-to-surface |
| 8. B $A_B M_S(2) N_S(3)$ | borehole-to-surface |
| 9. B $A_B M_S(3) N_S(4)$ | borehole-to-surface |
| 10. B $A_S(-4) M_B N_B$ | surface-to-borehole |
| 11. B $A_S(-3) M_B N_B$ | surface-to-borehole |
| 12. B $A_S(-2) M_B N_B$ | surface-to-borehole |
| 13. B $A_S(-1) M_B N_B$ | surface-to-borehole |
| 14. B $A_S(0) M_B N_B$ | surface-to-borehole |
| 15. B $A_S(1) M_B N_B$ | surface-to-borehole |
| 16. B $A_S(2) M_B N_B$ | surface-to-borehole |
| 17. B $A_S(3) M_B N_B$ | surface-to-borehole |
| 18. B $A_S(4) M_B N_B$ | surface-to-borehole |

Ten transmitter electrode combinations must be energized for each sequence of measurements. Using a transmitted waveform period of 0.5 to 1 s, 5 to 10 s will be required for the sequence. If these measurements are made in a 1 m interval, a logging speed of 6 to 12 m per minute results. Electromagnetic induction effects, which are not accounted for in d.c.

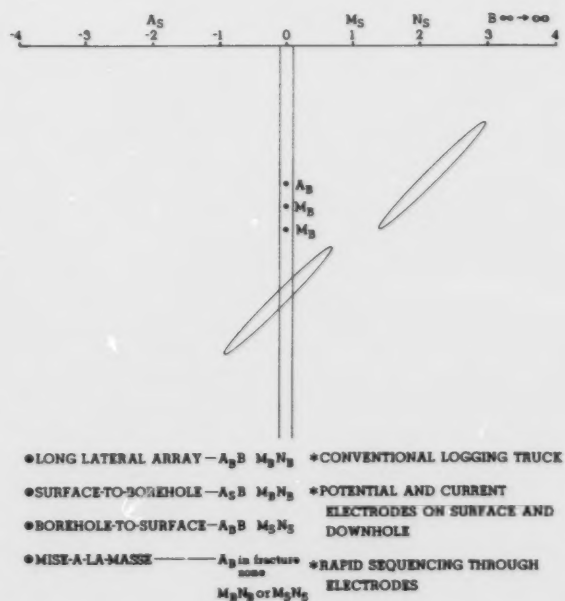


Figure 49.6. The multiarray borehole resistivity and induced polarization scheme, one borehole.

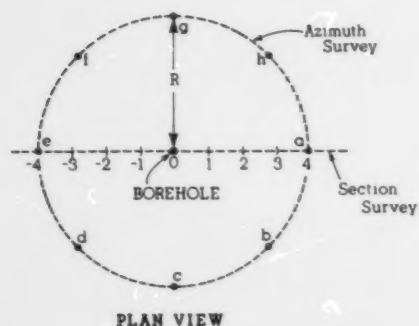
resistivity formulation, increase with frequency. The magnitude of these effects is not predictable. By testing the final system configuration, the shortest transmitter period which will result in the fastest logging speed without distorting the resistivity measurement will be chosen.

Referring to Figure 49.7, the electrodes AS, MS, and NS can be arranged in single section through the borehole for section surveys (electrode locations -4 through +4) or deployed at selected radial distances from the borehole for azimuth surveys (electrode locations a through h). The section survey in the surface-to-hole measuring mode is especially useful for determining depth to the centre of the body while the azimuth survey is useful for determining the direction to the body from the borehole and the strike of the body. The hole-to-surface measurement may be best for locating the lateral position of the body.

The mise-à-la-masse method is also accommodated by the multiarray. When the electrode A_B lies in the body, the body is directly energized. Then measurements of potential via $M_S N_S$ yield the conventional mise-à-la-masse result.

If more than one borehole is available, then cross-borehole measurements are also facilitated and mise-à-la-masse potential measurements can then be made in the subsurface as well as on the surface. Figure 49.8 illustrates a two-borehole multiarray. Rapid switching between all electrode pairs is then generalized from that presented earlier; the many options require systematic application.

With all of the electrode positions used, electrical "geotomography" may possibly be used in interpretation. We visualize three-dimensional data inversion to effect interpretation analogous to seismic geotomography, an idea first suggested to us by Jef-



LOCATIONS OF A_S : -4,-3,-2,-1,0,1,2,3,4 SECTION SURVEY
a,b,c,d,e,f,g,h AZIMUTH SURVEY

Figure 49.7. Azimuthal and section surveys with the multiarray borehole resistivity and induced polarization scheme.

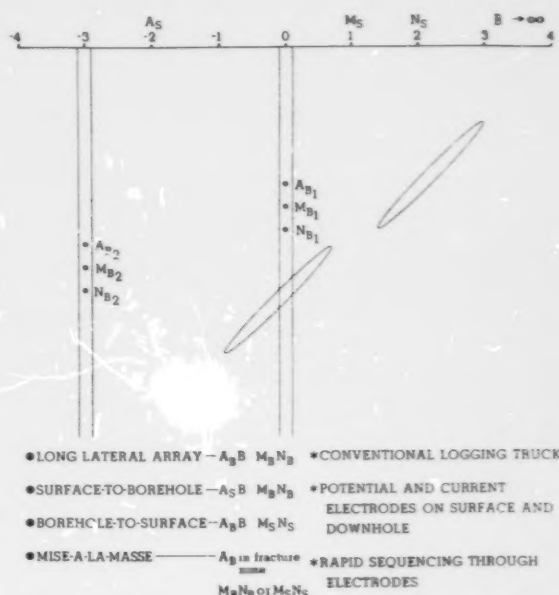


Figure 49.8. The multiarray borehole resistivity and induced polarization scheme, two boreholes.

frey J. Daniels of Ohio State University, Columbus, Ohio. There is a question, of course, as to the use of the word "geotomography" since it implies resolution approaching that of photography. Such resolution is not possible with the d.c. resistivity method.

Geological Noise

Using a finite-element algorithm which allows for subsurface current and potential electrodes in d.c. resistivity, Zhao *et al.* (1986) analyzed the detection of a thin, two-dimensional, conductive inhomogeneity in the presence of several sources of geological noise. The pole-pole array with the current electrode fixed in one borehole and the potential electrode movable in adjacent boreholes was the main array of concern. The sources of noise were surface topography, buried topography, random geological noise, quasi-random geological noise (nontarget inhomogeneities), layering, and a vertical contact. For several positions of a downhole source electrode, normalized apparent resistivities were computed. These resistivities were contoured in section view as appropriate to cross-borehole investigations.

For the models studied, surface topography, buried topography, random and quasi-random geological noise do not obscure the anomaly due to the thin, conductive inhomogeneity. However, for a thin, vertical, two-dimensional, conductive dike in a layered earth, an apparent resistivity low occurs around the source, (Figure 49.9a) not around the body. On the other hand, when this apparent resistivity is normalized by the apparent resistivity of the half-space, the resistivity low appears much closer to

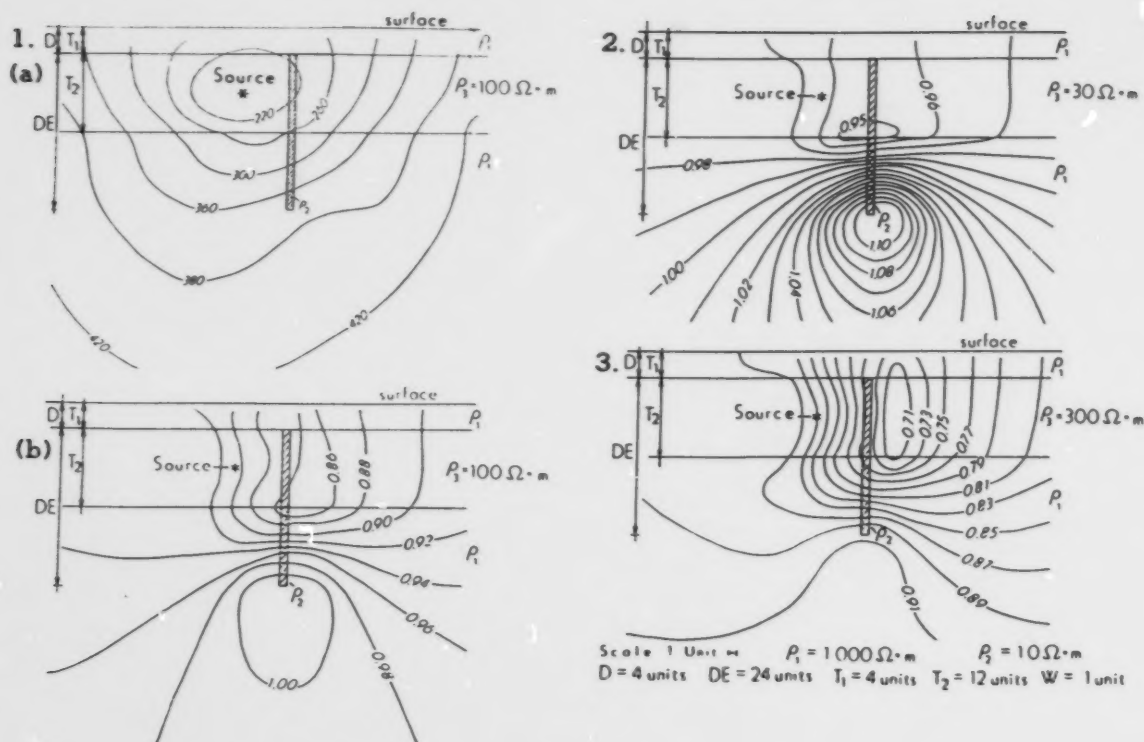


Figure 49.9. (a) Apparent resistivity for a thin, two-dimensional, conductive dike in a layered earth, data not normalized. (b) 1. Apparent resistivity contours for a thin, two-dimensional, conductive dike in a layered earth, apparent resistivity normalized by apparent resistivity of a layered earth, resistivity of second layer 100 ohm-metres; 2. Resistivity of second layer 30 ohm-metres; 3. Resistivity of second layer 300 ohm-metres (after Zhao et al. 1986).

the two-dimensional body as shown in Figure 49.9b(2), and 49.9b(3). Similarly, for a thin, two-dimensional body at a vertical contact (Figure 49.10a) an apparent resistivity low occurs around the source. While a normalization procedure could also be employed in this instance, a much more practical approach is to use a dipole-dipole cross-borehole survey as illustrated in Figure 49.10b. The advantage of the multiarray borehole resistivity and induced-polarization method is apparent here since it affords the opportunity to perform so many different arrays at the same time.

Effects of Casing

Apart from geological noise, the other potential source of significant noise would arise in steel casing in a borehole. While we are still studying this effect, a preliminary result suggests that this is not a major problem. Figure 49.11 shows the borehole profile of apparent resistivity for a long lateral array (100 m spacing) due to a nearby three-dimensional conductive body. Also shown is a profile of apparent resistivity due to the body plus the steel casing. The casing extends from the surface to 55 m depth and was given a $\sigma_{rt} = 150\,000$ mhos-m, where σ is conduc-

tivity, r is radius, and t is wall thickness; the radius of the casing is 0.11 m. The body is offset 100 m from the borehole, is 100 m thick, and is 1000 m in each of its other two directions. The plotting position is that of the potential electrode (M) nearest the subsurface current electrode (A). Once the far potential electrode (N) begins to exit the borehole, there is a large excursion in the apparent resistivity; this effect only persists until potential electrode (M) is 150 m beneath the bottom of the casing. Thereafter the effect of the three-dimensional body is clearly seen. We conclude that the effect on a long lateral array is not a major problem.

For the borehole-to-surface configuration, the effect of the casing increases as the surface potential dipole moves closer to the casing. Figure 49.12 illustrates the borehole apparent resistivity profiles for a 100 m surface dipole centred 500 m from the top of the borehole. A single current electrode is run down the borehole with the return current electrode at infinity. The casing runs from 0 to 500 m and its parameters remain unchanged, although the centre of the top edge of the body is offset 200 m from the borehole and the body extends from 250 to 125 m. Again the effect of the casing does not extend more

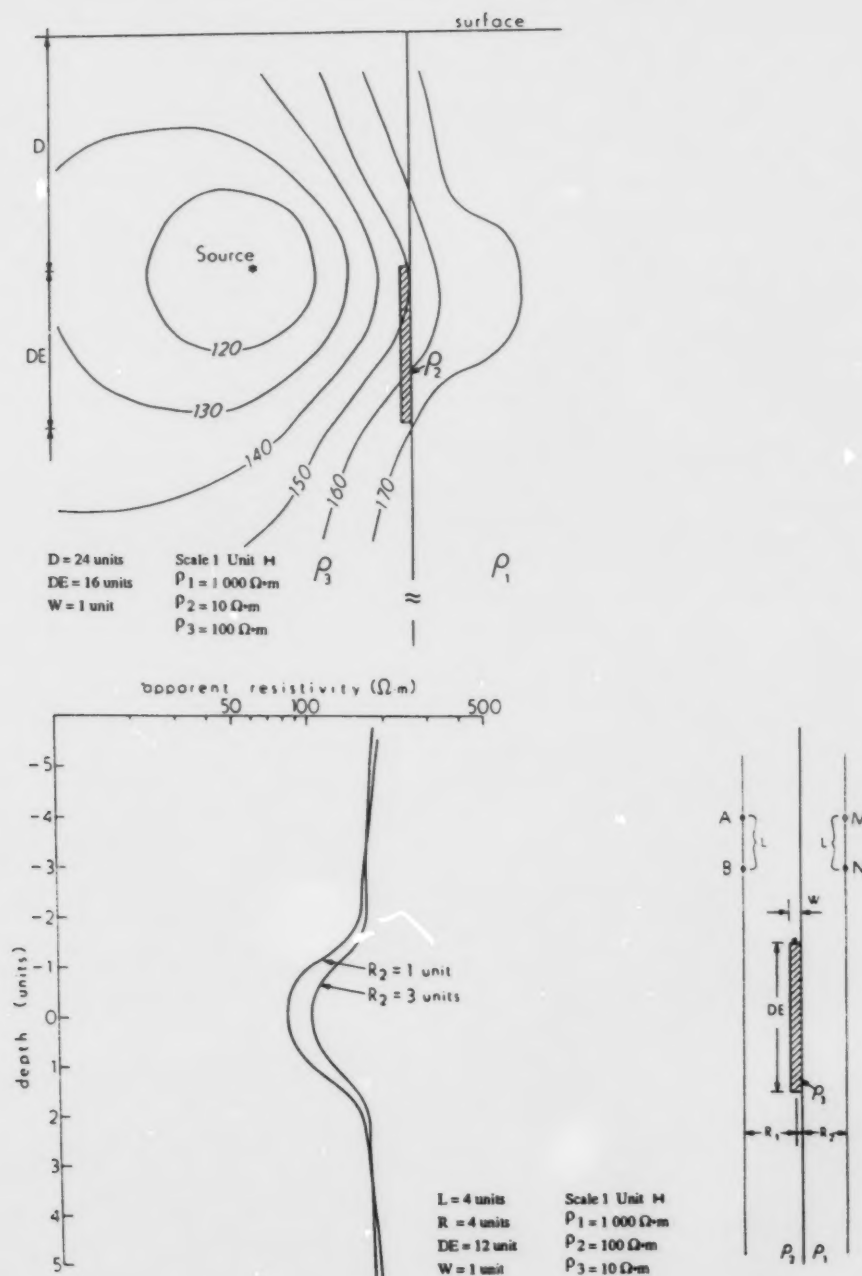


Figure 49.10. Apparent resistivity for a dipole-dipole crossborehole survey near a thin, two-dimensional, conductive dike at a contact.

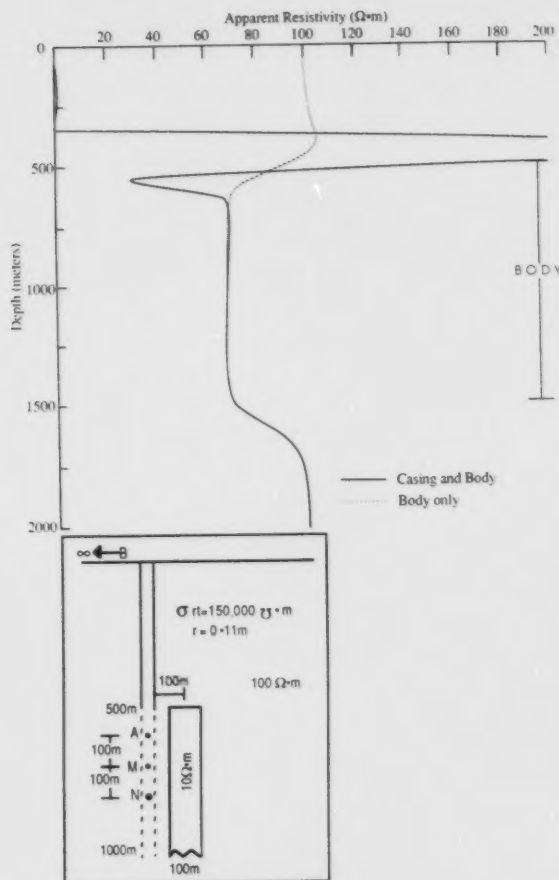


Figure 49.11. Borehole apparent-resistivity profile for a 100 m lateral array down a borehole cased to 500 m. A three-dimensional body lies adjacent to the borehole as shown in the figure.

than 150 m from its bottom. The anomaly due to the body is clearly seen. As long as several dipole receivers are used on surface, with varying distances from the borehole, then numerical modeling will readily permit recognition of the body in the presence of the casing.

ACKNOWLEDGMENTS

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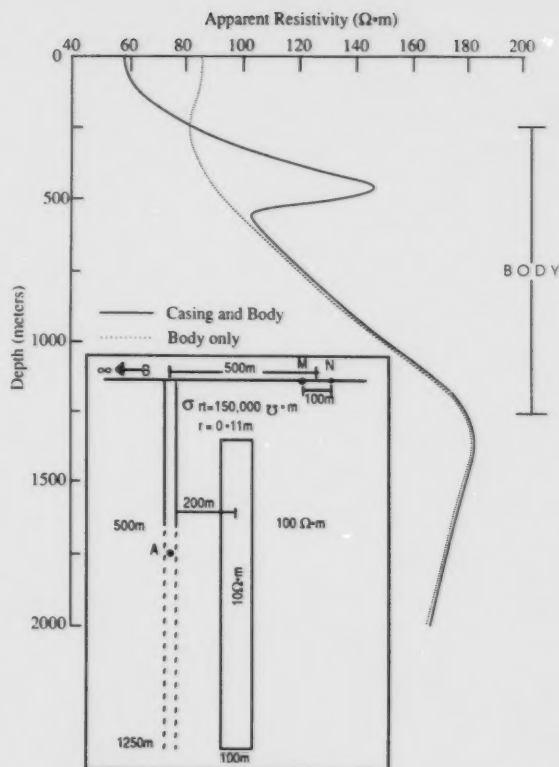


Figure 49.12. Borehole apparent-resistivity profile for a pole source downhole and a 100 m receiving dipole at surface. The borehole is cased to 500 m; all parameters are shown in the figure.

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50. Mineral and Rock Geochemistry in Geothermal Exploration

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ABSTRACT

High-temperature geothermal systems are currently being exploited in many parts of the world for electric power. The exploration and development of these resources requires a multidisciplinary approach that includes geoscientific, engineering, and economic analyses. Petrologic and geochemical studies of geothermally altered rocks and soils often assume particular importance during the early stages of an exploration program, when little is known about the size, shape, and temperature of the geothermal reservoir. In this paper, we describe the secondary mineral distributions and trace and major element dispersion patterns characteristic of high-temperature geothermal systems and illustrate their application to the assessment of such systems.

INTRODUCTION

Geochemical investigations of soils and geothermally altered rocks can frequently supplement data obtained from borehole measurements and the evaluation of fluid geothermometers. During the evaluation of a geothermal field, studies of the altered rocks aid in understanding the geologic features that control reservoir permeabilities, the temperature distributions at depth and the origin, flow directions, and composition of the reservoir fluids. Such information is particularly important when the wells fail to discharge fluids or the fluids produced are contaminated or altered to such an extent that their original higher temperature subsurface characteristics are no longer discernible. In this paper we review the mineralogical and geochemical characteristics of high-temperature (>200°C) liquid-dominated geothermal systems. Such systems are important producers of electricity in many parts of the world. In contrast, lower temperature geothermal systems are generally used for space heating or industrial process heat.

GEOLOGIC CHARACTERISTICS OF GEOTHERMAL SYSTEMS

Most high-temperature geothermal systems are associated either with active andesitic stratovolcanoes (e.g. the Cascades and Garibaldi volcanic belts of the U.S. and Canada) or young silicic volcanic fields (e.g. Coso, California, and the Taupo volcanic zone, New Zealand). Schematic geologic models of geothermal systems in these environments are illustrated

in Figure 50.1. These geothermal systems are dominated by a deep, reservoir containing near-neutral pH NaCl fluids. Fluid movement within the reservoir rocks is controlled primarily by steeply dipping faults and fractures. In both cases, heat is supplied to the geothermal system by young, deeply buried magma bodies and is transferred by convection within the reservoir. Surface outflow of the deep reservoir fluids may occur at distances of up to several kilometres from the hottest portions of the geothermal system as boiling springs associated with silica (sinter) deposits. Boiling is also common in the upper portions of many high-temperature geothermal systems. Steam and acidic gases (primarily CO₂ and H₂S) released from the deep reservoir may condense in the overlying groundwaters giving rise to chemically distinct bicarbonate and sulphate-rich fluids. These groundwaters may vent at the surface as travertine (calcium carbonate) depositing springs. Alternatively, fumaroles may discharge the steam and gases at the surface. These vent areas are often associated with spectacular zones of advanced argillic alteration caused by sulphuric acid produced at the surface.

ALTERATION MINERALOGY

Geothermal systems are characterized by a relatively simple suite of secondary minerals (Browne 1978). Most are dominated by mineral assemblages consisting primarily of sheet silicates, quartz, carbonate, and feldspar. Browne (1978) concluded that the distribution of the secondary mineral assemblages found in active geothermal systems is controlled by six factors: temperature, fluid chemistry, pressure, permeability, rock type, and time. Although it is generally difficult to separate the effects of individual factors, temperature, and to a lesser extent, fluid chemistry and permeability appear to be the most significant.

MINERAL DEPOSITION RESULTING FROM COOLING

Mineral deposition may occur as a result of cooling, heating, or boiling. Cooling of thermal brines may occur conductively, by mixing with lower temperature fluids, or as a consequence of boiling. Cooling of the geothermal fluids typically leads to the precipitation of silica, silicates, oxides, and sulphides. Figure 50.2 illustrates the general temperature range of the common silica and silicate minerals found in active thermal systems. In general, three different

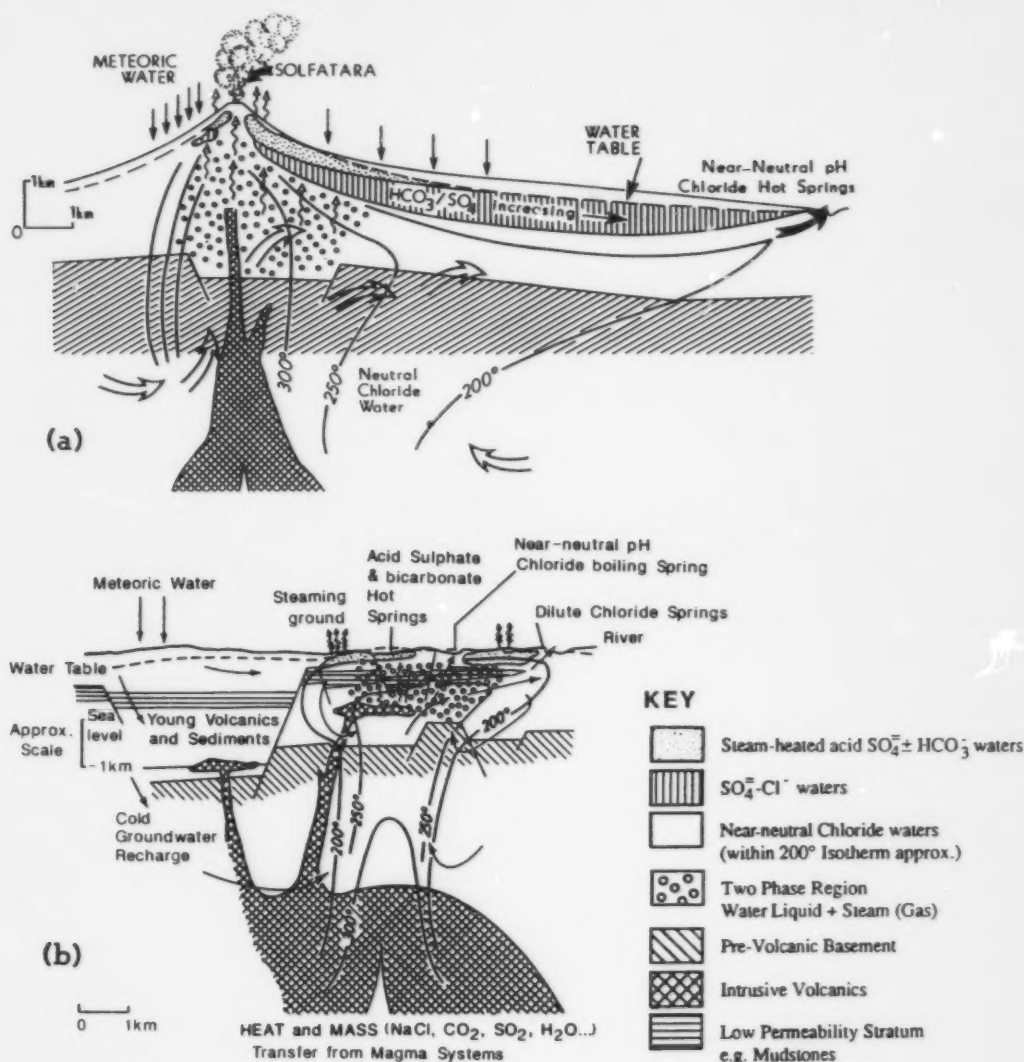


Figure 50.1. Schematic geologic models of high-temperature geothermal systems. (a) Andesitic stratovolcano with high relief and substantial recharge. (b) Silicic or bimodal volcanic terrains (from Henley and Ellis 1983).

temperature zones can be delineated: a) a low-temperature zone below about 200°C dominated by smectite and mixed-layer clays; b) an intermediate-temperature zone between 200 to 300°C characterized by epidote, illite, and chlorite; and c) a high-temperature zone above 300°C in which amphibole, pyroxene, biotite, and garnet become stable.

The chemistry and structure of the clay minerals in geothermal systems have been documented by Browne and Ellis (1970), Steiner (1968, 1977), McDowell and Elders (1980), and Liou *et al.* (1985), among others. McDowell and Elders (1980) provide a detailed account of the chemical changes of the sheet silicates during alteration in the Salton

Sea geothermal field located in the Imperial Valley of the U.S.

The mixed-layer clays found in the low-temperature zones include both interlayered illite/smectite and chlorite/smectite. Both random and ordered interlayered mixtures may be present. The relationships among the clay minerals described by Liou *et al.* (1985) from the Onikobe geothermal system in Japan appear to be representative in many aspects. The Onikobe geothermal area is located in northern Honshu, Japan. The field is associated with a caldera, approximately 10 km across, composed of andesitic and dacitic lavas and tuffs. Temperatures up

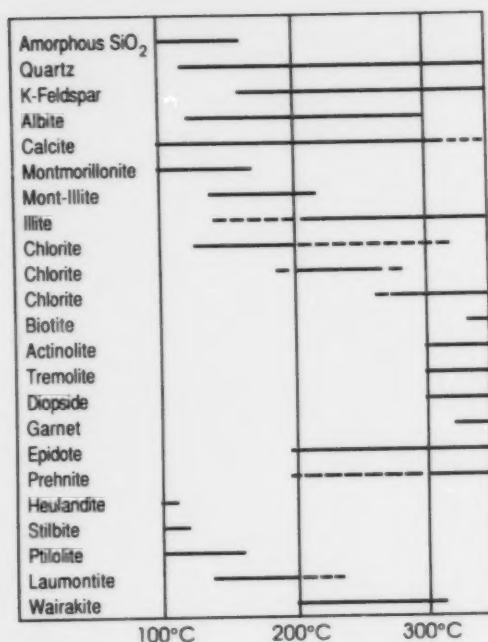


Figure 50.2. Temperatures over which the common secondary minerals in active geothermal systems have been observed. The three temperature ranges shown for chlorite refer to swelling, mixed layer, and non-swelling varieties (from Henley and Ellis 1983).

to 240°C have been encountered at depths of 1150 m.

The clay minerals at Onikobe are strongly zoned with respect to temperature and depth. At shallow depths above about 200 m, the clays include smectite (Mg and Ca rich), alkaline smectite (Na and K rich), and kaolinite. At greater depths the dominant clays are interlayered chlorite/smectite and chlorite. Interlayered illite/smectite and illite are also present, but are less abundant than they are in more silicic volcanics. In the silicic rocks occurring in the New Zealand geothermal fields, Ca-smectite is stable up to temperatures of about 140°C, followed by interlayered illite/smectite and finally illite above 220°C. Chemical and X-ray data from both the New Zealand and Japanese systems indicate that the smectite component of the interlayered illite/smectite and chlorite/smectite minerals decreases with increasing temperature until chlorite and illite become stable above 220°C. At temperatures below about 225°C, the common secondary minerals associated with near-neutral pH waters also include quartz, potassic feldspar, albite, sphene, pyrite, and zeolites. Although these minerals crystallize over a broad temperature range, the minimum temperatures for the formation of both feldspar and sphene appears to be near 150°C. In contrast, mineral assemblages produced by low-temperature acid waters include

amorphous silica, alunite, kaolinite, and dickite. At higher temperatures, minerals produced from acid waters that contain sulphate through oxidation or contact with sulphur include kaolinite, alunite, dickite, and pyrophyllite. However, the pH of these waters may not be much lower than about 5 (Ellis 1979). The low-temperature acid alteration characteristic of near-surface boiling is discussed more fully below (see boiling). Mineral assemblages found in intermediate-temperature regimes (between 200 to 300°C) typically consist of various mixtures of quartz, albite, potassic feldspar, epidote, chlorite, illite, sphene, pyrite, base metal sulphides, and less commonly, wairakite and prehnite.

Chemical data on the calc-silicate minerals, epidote, wairakite, prehnite, and sphene, and on potassic feldspar are summarized by Bird *et al.* (1984). Their data from Cerro Prieto, Mexico, is representative of other thermal systems and indicate that while the compositions of wairakite, sphene and, potassic feldspar are generally homogeneous and nearly ideal, both epidote and prehnite are compositionally variable. For example, epidotes range in composition from 11 to 31 mole percent pistacite.

The occurrence of epidote may be strongly influenced by the CO₂ content of the fluid and in some systems with high CO₂ pressures, epidote may be absent.

The effects of CO₂ are well illustrated by the distribution of epidote (and wairakite) in the New Zealand fields at Broadlands and Wairaki (Browne and Ellis 1970). At Broadlands, where the molality of CO₂ is 0.15, the typical mineral assemblage consists of K-mica, potassic feldspar, and calcite. In contrast, the mineral assemblage characteristic of Wairaki is epidote, wairakite, and potassic feldspar. This mineral assemblage reflects the lower CO₂ molality of the Wairakei fluids (0.01).

Geothermal systems that have temperatures exceeding 300°C are relatively uncommon. The secondary minerals in these systems include orthosilicates, ring silicates, and chain silicates which are not present at lower temperatures. The common minerals are garnet, actinolite, tremolite, and diopside. The chemical characteristics of these minerals have been reviewed by Bird *et al.* (1984).

Talc, associated in places with saponite and biotite, has also been found in a few extremely high-temperature geothermal systems, such as the Salton Sea geothermal field where measured temperatures exceed 325°C (McDowell and Elders 1980). The characteristic assemblage above this temperature includes biotite, quartz, epidote, potassic feldspar, albite, talc, pyrite, vermiculite, and sphene. Traces of chlorite are present to approximately 360°C, whereas garnet is present only above this temperature. Generally, similar zoning patterns are typical of other high-temperature systems such as Lardarello, Italy, Cerro Prieto, Mexico, and the high-temperature fields in Iceland (Bird *et al.* 1984).

As expected, the distribution of the zeolite minerals is also strongly temperature dependent. Figure 50.3 illustrates the distribution of zeolites characteristic of basaltic rocks in Iceland. Kristmannsdottir (1976) has recognized four major zones characterized by the successive appearance of chabazite (Zone I), mesolite (Zone II), stilbite (Zone III), and laumontite (Zone IV). In contrast to the zeolites characteristic of mafic terrains, the zeolites occurring in rhyolites are typically high-silica phases such as mordenite and cinoptilolite (for example, at Yellowstone, Wyoming, U.S.A. (Keith and Muffler 1978; Barger and Beeson 1984)).

Sulphide minerals are found in trace amounts in most active geothermal systems. Although a wide variety of sulphide minerals have been observed in some fields, the most common sulphides are pyrite, sphalerite, galena, pyrrhotite, marcasite, and arsenopyrite.

MINERAL DEPOSITION RESULTING FROM HEATING

Although the solubility of most minerals decreases with decreasing temperature, the solubility of carbonate and sulphate minerals generally increases

with decreasing temperature. Thus these minerals are most likely to precipitate on the margins of active geothermal systems where the heating of non-thermal groundwaters can occur. Indeed, White *et al.* (1971) suggested that the deposition of carbonate and sulphates on the margins of liquid-dominated geothermal systems could ultimately reduce the permeabilities to the point where recharge of the system could be severely retarded. Under these conditions, discharge could then exceed recharge, leading to the formation of a vapour-dominated system.

The most common carbonates and sulphates include calcite, dolomite, and anhydrite, although a variety of other minerals in these groups have been identified. For example, Barger and Keith (1984) report the presence of aragonite, calcite, ankerite-dolomite, magnesite, and siderite in altered volcanic and volcanoclastic rocks from a 932 m deep well in the caldera of the Newberry Volcano, Oregon. These authors also provide detailed petrographic and chemical data on the alteration phases.

Both the carbonate and sulphate minerals occur over a relatively broad temperature range and, thus, neither group appears to have much potential as mineral geothermometers.

MINERAL DEPOSITION RESULTING FROM BOILING

Boiling appears to be a common phenomenon in active geothermal systems, and there is abundant evidence to indicate that it occurs in both near-surface and deep environments. Boiling may affect mineral deposition in several different ways. Ascending hot water which boils at shallow depth may lead to the formation of fumaroles and the formation of mineral assemblages typical of low pH conditions. The intense alteration associated with fumarolic activity is produced dominantly by the downward percolation of acid waters (Schoen *et al.* 1974). These waters are produced at the surface by the oxidation of H_2S in the condensate to form sulphuric acid. Acid alteration extends downward to the water table, where the fluids are neutralized and partially reduced. Acid-altered rocks found in many geothermal fields consist mainly of a siliceous residue composed of opal accompanied by alunite, kaolinite, montmorillonite, marcasite, native sulphur, and cinnabar.

Boiling at depth beneath the water table may lead to the formation of hydrothermal breccias and mineral banding in veins. Exsolution of CO_2 and H_2S during boiling can cause an increase in the fluid pH, a change in the oxidation state of the fluid, and a destabilization of the sulphide complexes. Drummond and Ohmoto (1985) conclude that these changes result in the successive precipitation of oxides (Fe_3O_4), sulphides (ZnS , Ag_2S), native metals (Ag , Au), carbonates ($CaCO_3$), and other sulphides and sulphates. Quartz (deposited as a result of increasing silica concentrations and decreasing temperature) and carbonate will be the dominant

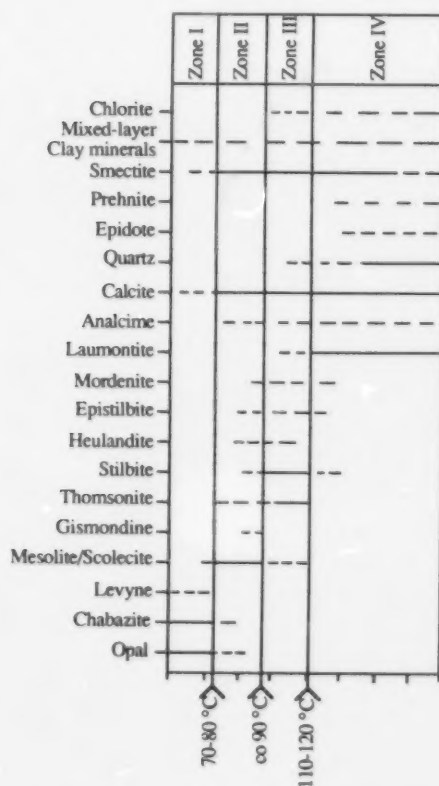


Figure 50.3. Temperatures over which secondary minerals characteristic of geothermal systems in basaltic rocks have been observed (from Kristmannsdottir 1976).

gangue minerals. Because most geothermal fluids are in equilibrium with potassic feldspar and K-mica at depth, changes in the pH produced by boiling may shift the stability field of the fluids into the potassic feldspar field, resulting in the deposition of vein adularia.

The condensation of steam and gases released from the boiling fluid in the overlying (non-boiling) fluids may both heat and decrease the pH of these groundwaters. Browne and Ellis (1970) have shown that such steam heating could lead to the precipitation of albite or K-mica.

TRACE AND MAJOR ELEMENT DISTRIBUTIONS IN GEOTHERMAL SYSTEMS

TRACE ELEMENT DISTRIBUTIONS IN ROCKS

Chemical analyses of drill samples indicate that many trace elements are leached, transported, and deposited even before appreciable alteration has become evident. Thus, chemical data can provide information that is not readily obtained using other methods.

Geothermal systems are commonly enriched in the same suite of trace elements found in many fossil epithermal deposits. Ewers and Keays (1977) published the first comprehensive study of trace element distributions in an active geothermal system. Their work, based principally on the chemistry of hot spring deposits, well bore precipitates, and geothermally altered rocks from two drillholes in the Broadlands geothermal area of New Zealand demonstrated that the near-surface rocks were enriched primarily in As, Hg, Sb, Au, and Tl. In contrast, silver and the base metals (Se, Te, Pb, Zn, Cu, and Co) were found to be enriched at depth. Adams and Moore (1987) have shown that Bi may also be concentrated in the upper portions of some geothermal systems.

The relationship between temperature and the distribution of Hg was investigated by Christensen *et al.* (1983) at Roosevelt Hot Springs, Utah. Three wells which provide an illustrative cross-section of the thermal field from the interior to the southern margin were studied in detail (refer to Figures 50.4(a,b) and 50.5(a,b)). Wells 14-2 and 72-16 are productive, well 52-21 is dry. The rocks in these wells consist of Tertiary granites and high-grade Precambrian gneiss.

The temperatures and distribution of Hg in these wells are shown in Figure 50.4b. Values in excess of 20 ppb define a broad envelope in the outer portion of the field whose base closely corresponds to the 215°C (420°F) isotherm.

The deposition and mobility of Hg at Roosevelt Hot Springs was also investigated by Christensen *et*

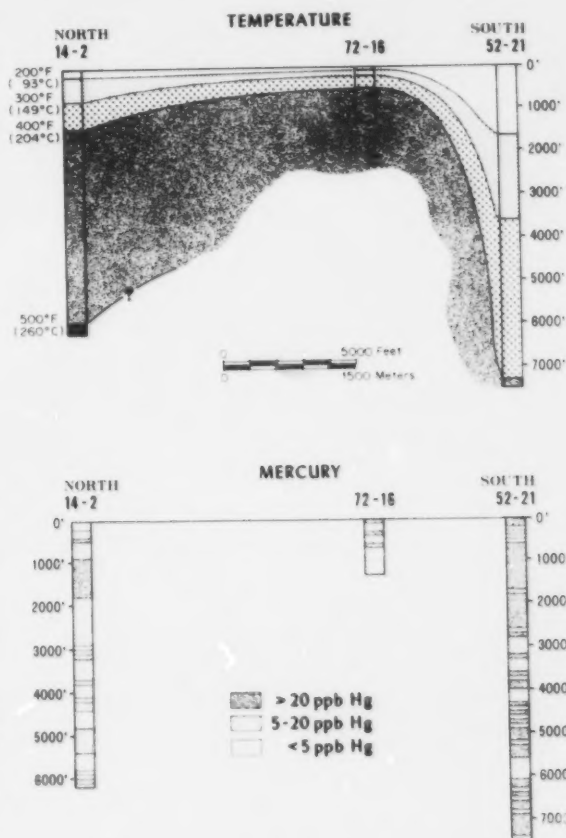


Figure 50.4. (a) Temperature distributions in wells 14-2, 72-16, and 52-21, Roosevelt Hot Springs, Utah. See Figure 50.5a for the locations of wells 14-2 and 72-16. Well 52-21 is located 2 km south of 72-16. (b) Hg concentrations in the three wells shown in Figure 50.4a (modified from Christensen *et al.* 1983).

al. (1983) by measuring the progressive loss of Hg from samples heated in air. The temperature of Hg release has been shown to be characteristic of the various mercury compounds and occurrences. For example, adsorbed mercury is mobilized at temperatures below 100°C, from silicate minerals at about 150°C, from cinnabar at temperatures mainly above 250°C, and from pyrite at temperatures generally above 450°C.

The release curves for Hg from Roosevelt Hot Springs samples suggest that Hg occurs in all four different forms. Samples from the upper parts of the wells released mercury at temperatures of less than 150°C. These data suggest that the majority of the Hg in the low-temperature portions of the field is primarily adsorbed on the altered rocks. Hg released at temperatures above 150°C was found in samples characterized by quartz veining suggesting that Hg may be contained in silicate minerals in these sam-

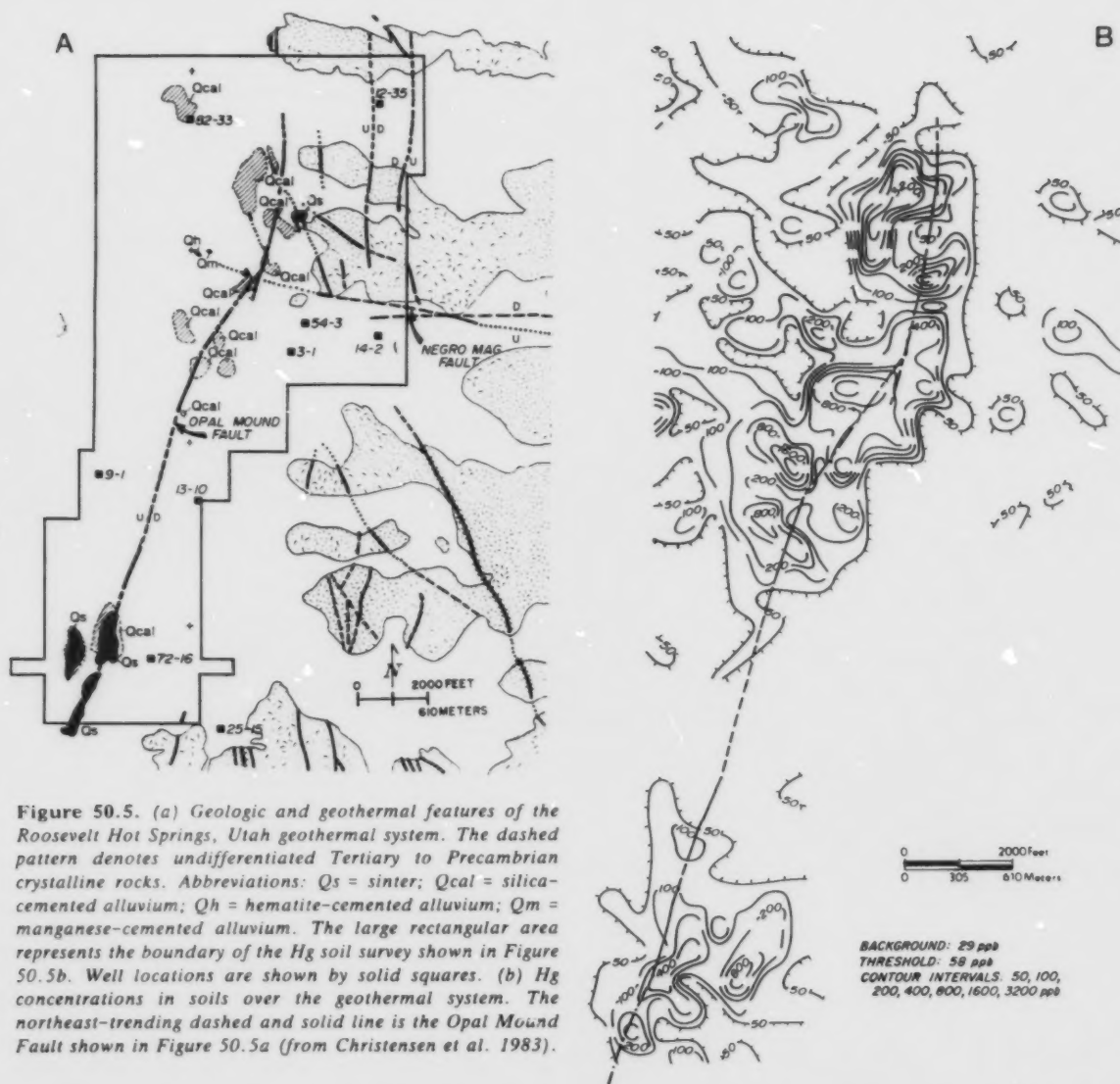


Figure 50.5. (a) Geologic and geothermal features of the Roosevelt Hot Springs, Utah geothermal system. The dashed pattern denotes undifferentiated Tertiary to Precambrian crystalline rocks. Abbreviations: Qs = sinter; Qcal = silica-cemented alluvium; Qh = hematite-cemented alluvium; Qm = manganese-cemented alluvium. The large rectangular area represents the boundary of the Hg soil survey shown in Figure 50.5b. Well locations are shown by solid squares. (b) Hg concentrations in soils over the geothermal system. The northeast-trending dashed and solid line is the Opal Mound Fault shown in Figure 50.5a (from Christensen et al. 1983).

ples. Release temperatures characteristic of cinnabar were found in only two samples, one from a sample of altered alluvium and the second from a deep well sample. The highest release temperatures are associated with pyritized samples. The release of mercury at temperatures in excess of 400°C is consistent with Hg residence in pyrite.

MAJOR ELEMENT DISTRIBUTIONS IN ROCKS

As expected, variations in the major element contents of geothermally altered rocks can be closely correlated with the distribution of secondary minerals. At Wairaki, Steiner (1977) showed that Ca and Na were depleted in nearly all the altered rocks whereas Si and K were enriched. In addition, Al, Fe, and Mg have been depleted in the high-tem-

perature zones. The enrichments in Si are related to the deposition of quartz, whereas loss of Na and Al, and enrichments in K appear to be related primarily to the destruction of andesine and the formation of potassium feldspar. Iron and Mg contained in clay is lost through their destruction and low temperatures.

TRACE ELEMENT DISTRIBUTIONS IN SOILS

Geochemical soil investigations have been utilized in a great many geothermal environments. In areas where the geothermal systems are poorly exposed at the surface, reconnaissance soil surveys have defined the overall limits of the thermal system. Elsewhere detailed soil investigations have been used to delineate the distribution of permeable fault zones which extend from the surface to the thermal reservoir.

Investigations of soil chemistry generally fall into one of several types: 1) detection of Hg adsorbed by the soil; 2) detection of non-volatile elements deposited by fluids which reach the surface; and 3) detection of soil gases. In this section we briefly review the application of these various methods and provide selected examples of their use.

MERCURY SOIL SURVEYS

Anomalous concentrations of Hg in soils over active geothermal systems have been noted by many workers (e.g. Matlick and Buseck 1976; Capuano and Bamford 1978; Klusman and Landress 1978, 1979; Christensen *et al.* 1983; Varekamp and Buseck 1984). In general, these studies indicate that Hg soil surveys define broad areas having potential as geothermal resources but that the results are highly dependent on local geologic conditions.

The relationship between soil geochemistry, heat flow, faulting, and subsurface movement of the geothermal fluids in shallow aquifers is well illustrated by studies of the Roosevelt Hot Springs geothermal system (Capuano and Bamford 1978; Christensen *et al.* 1983). Figure 5b shows the distribution of Hg in an 11 km² area over the thermal system. Log-normal cumulative frequency plots show that at least two populations of Hg occur in the Roosevelt Hot Springs soil data. These plots define a background value of 29 ppb and a threshold value of 58 ppb Hg for the area. Anomalous concentrations of Hg in soils over the system occur in a series of closely spaced northeast- and northwest-trending zones that parallel major fault directions in the geothermal field (see Figure 50.5a). Zones of high permeability, characterized by extreme enrichments of Hg, occur at the intersections of these structural trends and are frequently coincident with hot spring deposits. Extension of the anomalous Hg concentrations to the northwest occurs beyond the known limits of the reservoir and appears to reflect the release of Hg vapour from thermal fluids flowing within shallow alluvial aquifers down the local hydrologic gradient. This flow is documented as well by an extension of the shallow thermal anomaly to the northwest and by concentration gradients in the chemistry of the regional groundwaters.

NON-VOLATILE ELEMENTS IN SOILS

Unfortunately little data has been published on the distribution of non-volatile elements in the upper few tens of metres of active thermal systems. Geochemical studies at Roosevelt Hot Springs, described below, indicate that any surficial remobilization that has occurred is closely related to areas where hot springs and fumaroles discharge. Predictably, enrichments in non-volatile elements appear to be restricted to relatively high-temperature geothermal systems.

At Roosevelt Hot Springs, the concentrations of As, W, and Sb in the soils appear to be slightly enriched in the vicinity of the hot spring deposits, whereas the concentrations of Mn, Cu, and Zn are lower (Capuano and Moore 1980). Lovell *et al.* (1983) suggested that Cs in addition to As and Sb was also enriched in the surface micro-layer at Roosevelt Hot Springs and that sampling of this material was also useful during geothermal exploration. These enrichments and depletions appear to reflect different processes; one to deposition by outflowing brines, and the second to leaching of near-surface rocks by downward-percolating acid sulphate waters which accompanied a declining water table.

The deposition of Mn-rich precipitates has occurred at several places at Roosevelt Hot Springs. The precipitates occur where metal-charged groundwater has emerged as springs downslope from the hot spring deposits (Capuano and Moore 1980; Christensen *et al.* 1983). The precipitates contain high concentrations of Mn (18.8%), Co (28 ppm), W (2940 ppm), Ba (4.9%), As (858 ppm), Sb (291 ppm), Be (18.6 ppm), and Hg (2210 ppb).

SOIL GAS SURVEYS

A variety of soil gases including Rn, He, S, Hg, CO, and CO₂ have been studied as possible exploration guides to active geothermal systems. Like the other methods described above, the application of soil gases to exploration is highly dependent on local geologic conditions. Consequently, these studies have frequently met with limited or guarded success.

Because of the very extensive data base available at Roosevelt Hot Springs, this area was chosen by both Nielson (1978) and Hinkle (1980) to study the behavior of Rn and He in soils over a high-temperature geothermal system. The Rn data show that closely spaced sampling can be used to map the location of faults that communicate with the reservoir in this field. The relationship between He in soil gas to the distribution of known and inferred faults is less obvious. The He data display a series of isolated anomalies near the center of the system, but in other areas of the field where both Rn and Hg are enriched, no He anomalies were detected. The reasons for these differences are not yet understood.

SUMMARY OF GEOCHEMICAL OBSERVATIONS

In the preceding pages we have reviewed some of the geochemical observations that can be made at various stages in the exploration and development of a geothermal system. The data described suggest that temperature and to a lesser extent fluid chemistry, pressure, rock type, and permeability are the main factors controlling the mineralogy, trace and major element geochemistry, and soil geochemistry in a geothermal field. In general, the effect of each of these factors will vary from field to field and often

even within a field. For example, while the pressures in the explored portions of active geothermal systems are relatively low, and consequently will have little effect on the mineralogy of the altered rocks, changes in pressure resulting in boiling may greatly affect mineral deposition and the fluid chemistry. Such zones will be found primarily in the more permeable portions of the system, and are likely to be characterized by veins containing quartz, carbonate, potassic feldspar (adularia), and perhaps sulphides. Zones of lower permeability will be characterized by areas of unaltered rock, even where temperatures are high. In these zones the fluids will not be in equilibrium with the rocks, and even thermally unstable phases such as volcanic glass may persist.

Figure 50.6 presents a generalized model of a geothermal system based on some of the relationships that have been described. Several possible fluid pathways are shown. Within the deep high temperature portions of the thermal system shown, fluid movement occurs predominantly along faults and fractures. In the upper parts of this geothermal field, lateral movement of the fluids is also important within the alluvium deposits. In volcanic terrains, the tops and bottoms of lava flows may also be important pathways for the lateral movement of the geothermal fluids.

As the fluids migrate through the thermal system, mineral deposition and sealing of the fluid pathways occurs as a result of cooling or boiling at various depths. In the deepest parts of the system (above 200°C) the fluid pathways are characterized by high-temperature minerals, such as chlorite, epidote, feldspars, and sulphides. Both the trace and major element contents of these altered rocks reflect this mineralogy. Enrichments in base metals, As, K, and Mg and depletions in Ca and Na may be found in this zone. At shallower depths (at temperatures less than 200°C), clays, quartz, and carbonate minerals become the dominant alteration phases. In

these rocks, Hg may be adsorbed onto rock surfaces.

As the water rises toward the surface, hydrostatic pressure decreases sufficiently to permit boiling. In this model, three courses of fluid discharge are indicated. In the first, the geothermal fluid begins to boil at shallow depths. Siliceous sinters are deposited around the vents of the boiling springs. These deposits and zones of silica-cemented alluvium, inferred to be zones of past shallow boiling or fluid mixing, are characterized by concentrations of As, Sb, Be, and Hg. This same suite of trace elements is enriched within soils that have been invaded by the thermal fluids. CO₂-charged waters may, in contrast, precipitate travertine (calcium carbonate deposits) at the surface.

In the second possible course, the thermal waters do not reach the surface. Boiling beneath the surface results in the release and separation of water vapour, Hg, CO₂, H₂S, and other gases from the thermal brines. As acid sulphate waters form from the H₂S and condensate at the surface and percolate downward, they leave a siliceous residue containing minerals characteristic of low pH conditions such as alunite and kaolinite. A similar process can occur near the hot springs as the water table declines. Subsequent oxidation of the downward-percolating waters can lead to the deposition of Mn and Fe oxides enriched in Ba, W, Be, Co, Cu, As, Sb, and Hg.

The Hg and S released from the boiling fluid may be deposited as cinnabar and native sulphur at the surface. Lower concentrations of Hg may develop in the surrounding soils by vapour transport as cooler non-boiling fluids migrate through shallow aquifers.

In the third illustrated fluid course, mineral precipitation within structures, leads to a nearly complete sealing of the fluid conduits, effectively interrupting fluid flow. If the cap is breached by tectonic or thermally induced fracturing or by drilling, sudden flashing of the fluid column may occur beneath it, leading to the precipitation of calcium carbonate.

Because of the different fluid-flow paths and different sequences of physical and chemical conditions encountered, one thermal brine may leave behind a variety of different chemical signatures and deposits. The recognition and understanding of these features can be of significant importance, not only for the exploration of active geothermal systems, but also for their fossil analogues, the epithermal precious metal deposits.

ACKNOWLEDGMENTS

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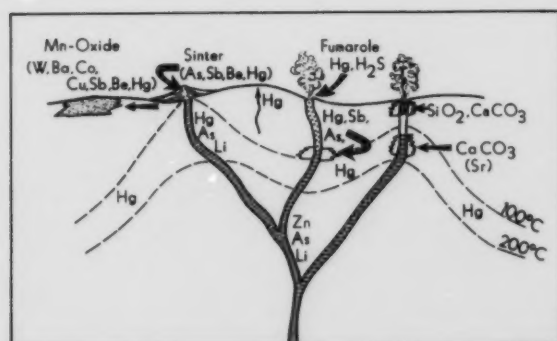


Figure 50.6. Schematic model of a geothermal system illustrating the relative positions of the principal geochemical features (from Christensen et al. 1983).

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51. Geophysical Well Logging Above the Water Table

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ABSTRACT

An understanding of near-surface physical properties is limited by poor core recovery and a restricted ability to measure *in situ* physical properties above the water table. Natural gamma ray measurements are currently the only *in situ* measurement that can be made reliably above the water table. Examples of geophysical logs from volcanic tuffs, igneous, and sedimentary rocks illustrate some of the problems of making measurements above the water table in fluid-filled holes. Neutron-neutron measurements in a hole that has been drained of water will yield values that are opposite to the responses obtained when the rocks are saturated. Conventional resistivity and acoustic geophysical well-log measurements require a water-filled drillhole. Electrical and acoustic property measurements can only be obtained above the water table in a dry hole with specialized tools (side-walled acoustic, or EM induction), or by logging a fluid-filled hole, immediately after drilling and before fluid drains from the drillhole. Dry-hole resistivity measurements may be used to compute porosity and saturation in certain rock types, using a modified form of Archie's Law.

Dynamic hydrogeological properties above the water table dominate geophysical parameters, and these properties depend upon rock type, weather cycles, and the geological setting of a given area. Geophysical logs from the study areas show that the zone near the water table is also a region of marked compositional changes in the rocks. Nuclear and electrical induction measurements may be used to interpret weathering and variations in mineralogy associated with short and long-range variations in the water table.

INTRODUCTION

Our present knowledge of near-surface physical properties of rocks is limited by the difficulty of obtaining core, or accurate *in situ* measurements. A lack of information in the literature concerning physical properties above the water table is testimony to the fact that investigators have been primarily concerned with economic targets that are below the water table, while the region above the water table has long been ignored by geophysicists. Commercial logging companies in the petroleum industry usually do not make measurements in the upper sec-

tion of a drillhole, which often leaves the upper 100 or 200 m unlogged. However, physical properties above the water table are important for a number of reasons. First, many "noise" problems encountered by geophysicists are caused by near-surface variations in physical properties. Second, physical properties variations in the near-surface region reflect seasonal and permanent changes in the history of the water table. Third, knowledge of near-surface physical properties is necessary to accurately predict the hydrogeological properties.

Physical property characteristics for all rock types change markedly above the water table, in the unsaturated, or vadose zone. In fact, procedures for measuring and interpreting most of the important geophysical parameters below the water table must be modified for use above the water table. A summary of some of the restrictions on field measurement techniques for measuring physical properties above the water table is given in Table 51.1.

GEOPHYSICAL WELL-LOG RESPONSES ABOVE THE WATER TABLE

The response of nearly all geophysical well-logging tools is changed when the probe crosses the water table boundary. In some cases the change in probe response is barely perceptible, while in other cases measurements cannot be made above the water table. The response of some common types of geophysical logging tools is presented in the following discussion.

GAMMA RAY

Gamma ray measurements (total count, or spectral) are the most common measurements made above the water table. The response of the gamma ray probe is only minimally affected by the water table, and measurements above the water table can be confidently correlated with measurements below the water table.

The response of the natural gamma ray log in dry holes and holes containing steel casing has been well documented in the literature. Figure 51.1 illustrates the relative gamma ray response above and below the water table, and in a steel-cased hole versus an open hole. These logs show that the effect of casing and fluid in the hole is negligible for lithologic identification and stratigraphic correlation.

The character of the gamma ray log is influenced by a variety of factors, including:

TABLE 51.1. SUMMARY OF PHYSICAL PROPERTY MEASUREMENTS IN UNSATURATED ROCKS ABOVE THE WATER TABLE.

Measurement	Comments
Natural gamma ray	Reliable measurements can be obtained by applying a small linear correction factor for a dry hole and casing effects.
Resistivity/conductivity	Standard measurements difficult in a dry hole. Induction tools to measure the low conductivity of partially saturated rocks are needed.
SP/Induced Polarization	Cannot be made without making good electrical contact with the borehole wall.
Neutron-neutron	Residual changes in rock properties resulting from the drilling process, environmental effects in an air-filled borehole, and casing are very difficult to compensate for, resulting in unreliable data.
Acoustic velocity	Standard tools (including televiwer) will not work. Must use a device that is acoustically coupled to the borehole wall.
Gamma-gamma density	Reliable measurements can be obtained with a standard probe that is calibrated for a dry hole.
Nuclear activation	Must calibrate for a dry hole and casing. Some elements may be impossible to analyze through casing.
Magnetic Susceptibility	Excellent measurements can be obtained in open, or PVC cased, holes.

1. lateral variations in rock type
2. fluctuations in the water table
3. the structural history of a region

Radioactive minerals are often leached out of the weathered zone and concentrated in fracture coatings and fillings, in the water table and perched water levels, in clastic shales and clays, and in fault zones. The gamma ray log shown in Figure 51.2 is typical and exhibits low values in the leached granitic rock above the water table, a sharp peak at the water table, and moderate to high values below the water table.

Although Figure 51.2 shows a typical response, other responses are often encountered, as illustrated in Figures 51.3 and 51.4. An example showing the base of the weathered zone coinciding with the water table, and having lower gamma ray values below the

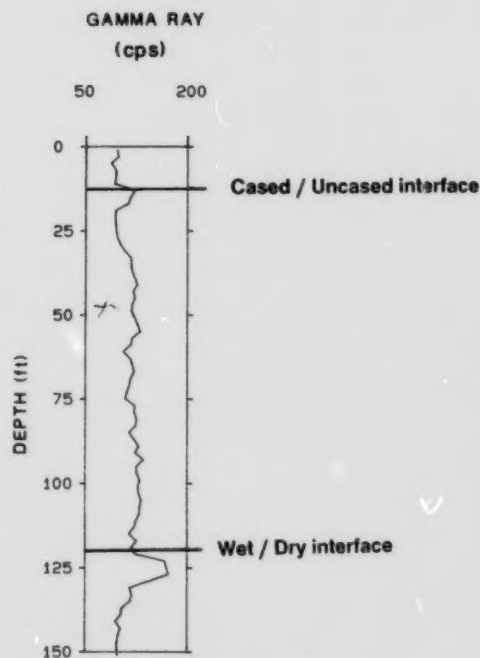


Figure 51.1. Relative response of a natural gamma ray probe across the wet-dry interface in a drillhole, and a cased-uncased section of a drillhole. Log is from welded tuffs in Nevada.

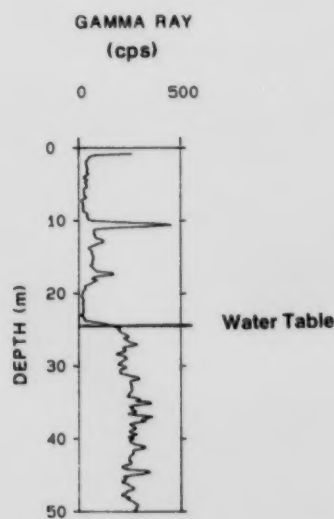


Figure 51.2. Typical gamma ray response at the water table boundary.

water table is illustrated in Figure 51.3. These holes were drilled in nearly vertically fractured limestone layers. Clean limestone typically exhibits very low gamma ray log values. The high values above the

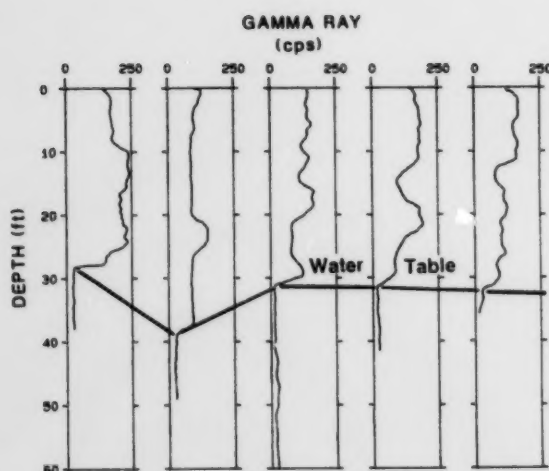


Figure 51.3. Total count gamma ray logs in fractured limestone (data courtesy of Technos Inc., Miami, Florida).

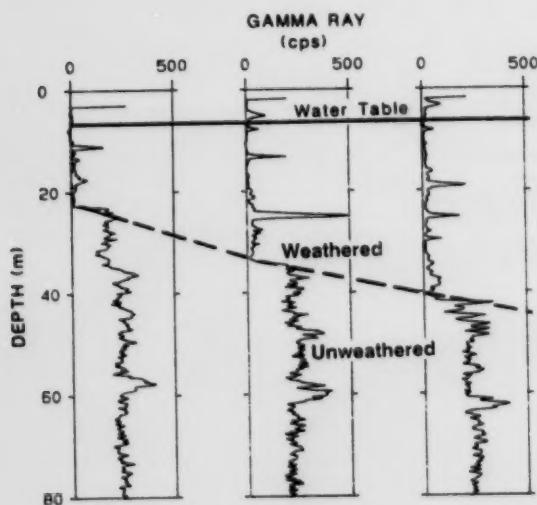


Figure 51.4. Total count gamma ray logs in granite illustrating the change in response across the water table and the weathered zone. Spacing between drillholes is approximately 10 m.

water table are from clastic sediments which fill the fractures in the weathered zone.

The base of the weathered zone does not always coincide with the water table. This is illustrated in Figure 51.4 where the water table is much closer to the surface than the weathered zone in granite. The gamma ray log in the weathered zone in Figure 51.4 shows peaks at depths above the base of the weathered zone that may be caused by fracture zones or may be caused by temporal or permanent variations in the water table. The possibility of intermittent structurally-related changes causing the change in

the water table and the associated anomalous concentration of radioactive minerals is supported by the nearly 17 m vertical change in the depth of weathering over 20 m of horizontal distance.

RESISTIVITY

Conventional direct current-resistivity measurements must be made in a fluid-filled hole. Often this requirement can be met by filling the hole with water and measuring the resistivity before the fluid drains from the drillhole. An example of using this procedure in welded tuffs is shown in Figure 51.5. Resistivity values above the water table are not within the range of values from below the water table, reflecting the incomplete invasion of the fluid introduced into the hole after drilling. Filling the hole with fluid after drilling is generally an unreliable method for making accurate quantitative measurements above the water table.

Geophysical logs from a fluid-filled drillhole in unsaturated volcanic tuffs are compared with saturated core values from the paper by Anderson (1984) on Figure 51.6. A viscous polymer drilling fluid was continually pumped into the drillhole during logging operations to maintain a fluid-filled hole.

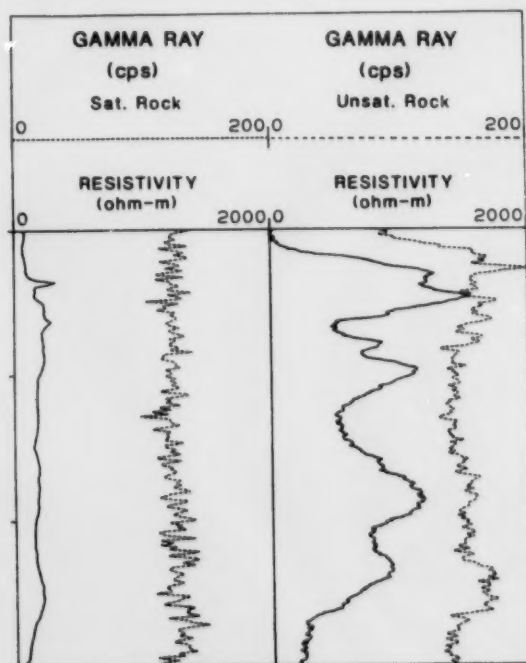


Figure 51.5. Normal configuration resistivity measurements (in ohm-m) above the water table made by filling the drillhole with water, and making the measurements before the fluid drained out (Unsat.) compared with measurements made below the water table (Sat.). Both sets of measurements were made in the same stratigraphic formation. Gamma ray measurements, in cps, are shown for reference.

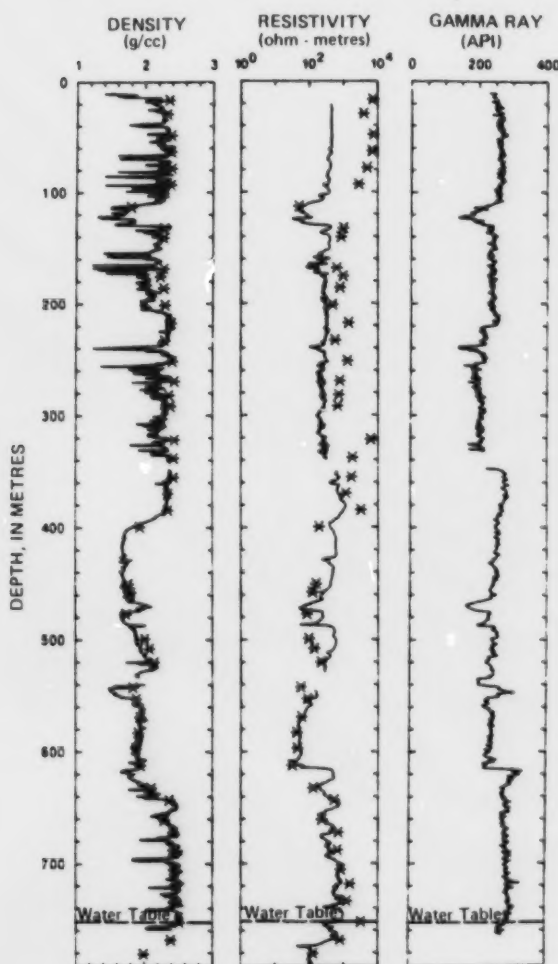


Figure 51.6. Density (in g/cm^3), resistivity (in ohm-m) and gamma ray logs (in cps) above the water table in a fluid-filled drillhole in volcanic rocks (core values from Anderson 1984).

The almost complete agreement between the density log and saturated core values throughout the drillhole indicates the rock has been artificially saturated with drilling fluid to at least the radius of investigation for the density tool. On the other hand, the conventional resistivity log shows three distinct intervals based on the comparison with core measurements. Below a depth of 540 m, agreement with the saturated core values indicates saturation with drilling fluid to at least the radius of investigation for the resistivity tool, which is much larger than the radius for the density tool. Higher resistivities occur in the intermediate region (400 to 540 m), than in the core. This is consistent with the lower density which indicates the rock is porous and permeable, allowing the drilling fluid to seep away from the drillhole without completely saturating the rock to the radius

of investigation of the resistivity tool. Resistivity values lower than the core values occurring above 400 m are primarily the result of core sample selection. The low-density spikes in this upper interval are the result of intense fracturing and, in some instances, the presence of up to softball-size voids called lithophysae. Unlike the *in situ* rock, the core samples selected for laboratory measurements are unfractured and lacking lithophysae. This results in biased core values which are evident on both the density and resistivity comparisons. The bias is enhanced for resistivity by the effect of drilling fluid in the fractures which tends to short-circuit the flow of electric current through the fractures instead of through the rock, resulting in a measured resistivity that is much less than the saturated core resistivity. The lower density and lower resistivity values from 110 to 130 m represent a bedded tuff occurring between the welded tuffs which accounts for the agreement of both logs with saturated core.

The interval from 400 to 620 m exhibits a distinctively lower density which increases with depth, while the corresponding saturated resistivity decreases with depth. This is not consistent with uniform mineralogy. Examination of the core in the interval reveals alteration to clays and zeolites increasing in abundance with depth (Scott and Castellanos 1984), which accounts for both the increase in density and the decrease in resistivity. The decrease with depth of measured gamma rays in the same interval indicates the possibility of leaching of radioactive minerals concurrent with alteration. A thin bedded tuff at 610 m (Scott 1977) acting as a permeability barrier to water enriched with radioactive minerals leached from the overlying rock then accounts for the abrupt peak in measured gamma rays above the higher-density, lower-permeability rock beginning at 640 m.

Occasionally, a resistivity array with four electrodes on the probe will drag along the side of the drillhole and intermittently give good quantitative results above the water table. An example of this is shown in Figure 51.7, where the measurements above the water level are erratic, but the general trend of the values is comparable to measurements below the water table. This example also illustrates the danger of using resistivity measurements to determine the depth of the water table. In general, the neutron-neutron log is a better indicator of the water table than the resistivity log. The occasional success of making resistivity measurements in dry holes by dragging the probe along the side of the drillhole suggests the possibility of forcing scratcher electrodes or fluid impregnated rollers against the side of the borehole to insure contact as illustrated in Figure 51.8.

The only way to insure accurate resistivity measurements in most dry holes is to use an induction (conductivity) probe. An example of induction logs above the water table in fractured limestone made

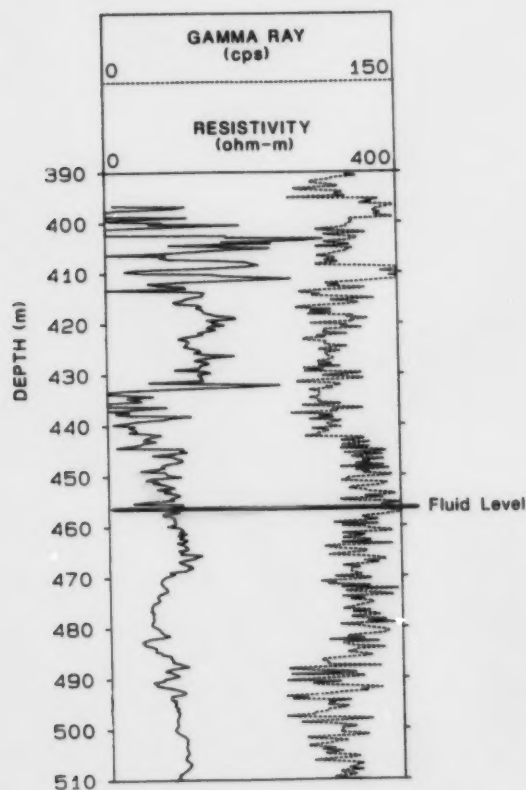


Figure 51.7. Direct current resistivity measurements (in ohm-m) extending above the water table by dragging the probe along the borehole wall. Neutron-neutron log (in cps) shows the true water table in this metamorphic formation.

with a Geonics EM-39 three coil induction probe designed for slimhole operation is shown in Figure 51.9. Conductivity values on these logs reflect the interpretation presented previously for gamma ray logs, with the fractured, weathered, limestone near the surface filled by high-conductivity clastic clays and sands. The primary problem with most induction probes is that they are limited to only the low resistivity range. Commercial multicoil induction probes designed for large-diameter petroleum holes are only accurate up to approximately 100 ohm-m, and the amount of measurement error of these probes increases markedly as resistivity increases above 100 ohm-m.

NEUTRON-NEUTRON

Neutron-neutron logs should be a direct measure of the hydrogen content of rocks, but several factors make neutron-neutron logs difficult to interpret above the water table. First, the neutron log measures hydrogen contained in chemically bound and interstitial pore water. In addition, neutron-neutron

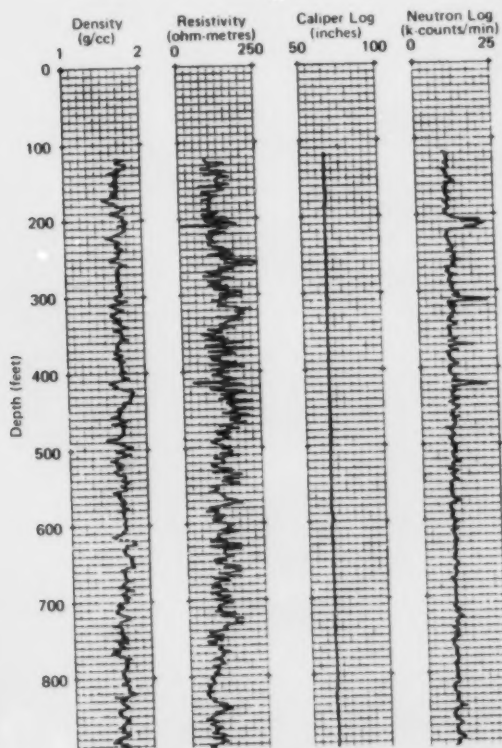


Figure 51.8. DC resistivity measurements (in ohm-m) in a large diameter drillhole in alluvium obtained with special copper sulphate impregnated rollers pressed against the side of the borehole wall. Density, caliper, and neutron logs are shown for reference (modified from Carroll and Muller 1973).

measurements are particularly difficult to interpret in zones of high porosity and permeability when water is injected into the rocks at the time of drilling. Water begins to drain from the hole immediately after drilling is completed, and the amount of water remaining in the rocks is initially proportional to the porosity of the individual rock units. Since fluid drains from porous formations faster than it drains from non-porous rocks, neutron log measurements made above the water table can lead to a totally erroneous interpretation. An example of this is shown in Figure 51.10 for neutron and density measurements made approximately 1 hour after drilling was completed. The density log correctly reflects the porosity of the welded tuffs, where the density and porosity are related to the degree of welding, while the neutron-neutron log response is the opposite of the expected result.

DENSITY

Density is one of the more reliable quantitative measurements above the water table. A calibrated density probe should yield the same degree of accu-

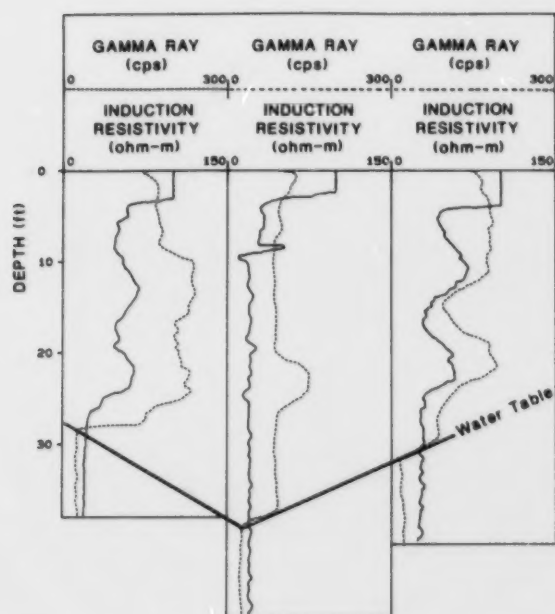


Figure 51.9. The response (in ohm-m) of a Geonics EM-39 induction probe in a fractured limestone above the water table. Gamma ray logs (in cps) from Figure 3 are repeated for comparison (figure courtesy of Technos Inc., Miami, FL).

racy in dry holes as it does in water-filled holes. In addition, Scott (1977) has shown that the difference between a wet and a dry-hole response is slight for some probes, but it can be significant if the probe is not shaped to fit the contour of the hole.

DETERMINING POROSITY AND SATURATION

Porosity and saturation are among the most important physical properties that can be determined from geophysical well logs. Empirical and experimental relationships between porosity and well log response for density, neutron-neutron, acoustic velocity, and resistivity are summarized in Table 51.2. These equations have been previously established in the literature and will not be discussed here in detail. An extensive discourse on the use of these equations above the water table in alluvium has been presented by Carroll and Muller (1973). The following discussion draws extensively on this work.

Wyllie's equation (Wyllie *et al.* 1958) for computing porosity from velocity measurements has been a mainstay since it was first reported in the literature. Unfortunately, velocity measurements require acoustic coupling between the rocks and the probe, which is only practical in fluid-filled holes. Dry-hole probes that utilize hydraulics to press sensors against

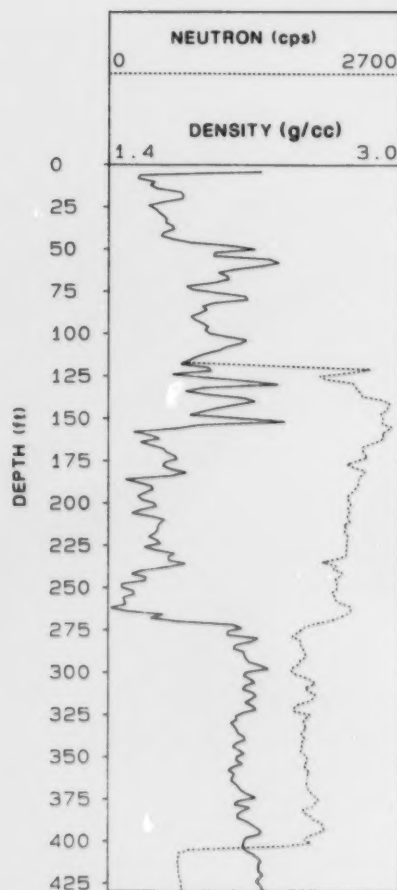


Figure 51.10. Neutron-neutron (in cps) and density (in g/cm³) logs above the water table, in welded tuffs, showing the response of the neutron log in rocks of different porosities.

the hole wall have been developed, but these measurements have only been made in specialized environments and it is doubtful if they are practical for all rock types.

The classic equation for determining porosity from saturated density and grain density is used extensively for measurements made in a fluid filled holes below the water table ($S_w = 100\%$). However, as Table 51.2 shows, porosity and saturation in dry holes cannot be determined uniquely from density alone.

Calibrated neutron-neutron measurements should directly yield the water content ($S_w\phi$) of rocks, making it possible to use a combination of neutron and density measurements to determine the porosity and saturation of rocks above the water table. Unfortunately, the effect of chemically bound water and fluid invasion on the neutron log response

TABLE 51.2. POROSITY AND SATURATION RELATIONSHIPS FOR COMMON LOGGING MEASUREMENTS.

Measurement	Porosity-Saturation Relationship	
velocity	$1/V = \phi/V_f + (1-\phi)/V_m$	(1)
density	$D_b = (1-\phi)D_g + (S_w\phi)D_f$	(2)
resistivity	$R_o/R_w = a\phi^{-m}$ (Archie's Law)	(3)
	$S_w = (R_o/R_t)^{1/n}$	(4)
neutron	response = $(S_w)\phi$	(5)

ϕ = effective porosity
 R_o = saturated resistivity
 R_w = pore fluid resistivity
 a = empirically determined constant
 m = cementation
 R_t = partially saturated resistivity
 D_b = density log value
 D_g = matrix density
 S_w = percent pore saturation
 D_f = pore fluid density
 V = velocity log measurement
 V_f = fluid velocity
 V_m = matrix velocity

ues of R_w less than 1 ohm-m. Experimentally determined values of R_w and R_o for alluvium in the study area (Figure 51.11) show that the R_o/R_w ratio is no longer constant when R_w exceeds approximately 3 ohm-m. This deviation is caused by surface charge effects that occur when the pore water resistivity is high and the rock contains minerals with a high cation exchange capacity. High cation exchange capacity clays and zeolites that contribute to surface conduction are present in the study area. Abnormally low values of R_o/R_w caused by surface conduction has the effect of yielding erroneous values of porosity from equation 3. To compensate for surface conduction effects, R_w in equation 3 can be modified to include an effective R_w that can be called R_{wa} . The validity of the saturation equation for the study area is illustrated from measurements on cores. This data, shown in Figure 51.12, demonstrates a near linear relationship between core sample resistivity and saturation. The break in the least squares line for each depth interval represents the natural-state sample. Resistivity values for saturations less than natural state were obtained by drying the sample, while values for saturations greater than natural state were obtained by adding tap water to the sample. If the line for saturations less than natural state is projected to where it intersects the vertical axis at a saturation value of 1, then the resulting value of R_o is much lower than is predicted by the data in Figure 51.11. In order to compensate for the anomalously low value of R_o , Archie's Law dictates that the effective R_w must be reduced. This is consistent with the results presented in Figure 51.11 and

precludes the use of neutron logs for the quantitative determination of porosity in dry holes.

The empirical basis for using resistivity for computing porosity expressed in Table 51.2 was introduced by Archie (1942) and has since become known as Archie's Law. The application of this equation requires the determination of the constants "a" and "m", and an independent measurement of R_w . Traditionally, "a" and "m" are determined experimentally from core, and R_w is computed from the SP log response. Since both the right and left sides of Archie's Law are constant, "a" and "m" may be determined directly from core without knowledge of the value for R_w . However, R_w must always be obtained independently before Archie's Law can be used to compute *in situ* porosity values.

Archie's Law only applies for saturated rocks, and the resistivity saturation equation in Table 51.2 must be considered. If R_t is measured with an induction, or a scratcher/roller probe, in a dry hole, then R_o and n in equation 4 must be determined in order to compute the saturation and porosity values of the rocks. The validity of equation 3 depends upon a linear relationship between R_o and R_w for freshwater resistivities greater than 1 ohm-m. This relationship has been experimentally established for val-

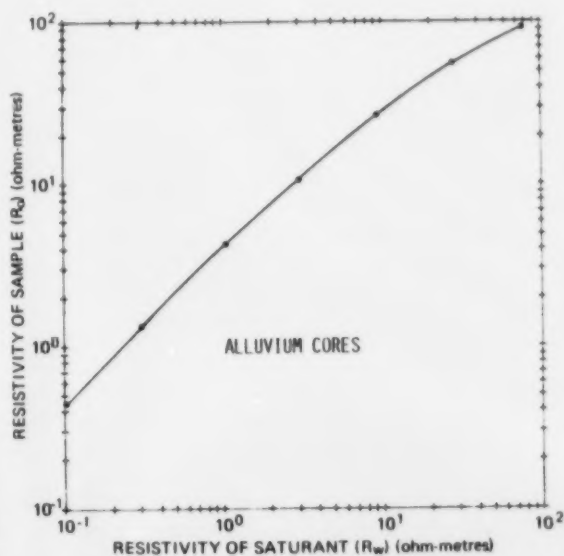


Figure 51.11. Variation of saturated resistivity (R_o) for various values of saturant resistivity (R_w) for a sample of alluvium (46 percent porosity) from a drillhole. Sample is from a depth of 467 feet (from Carroll and Muller 1973).

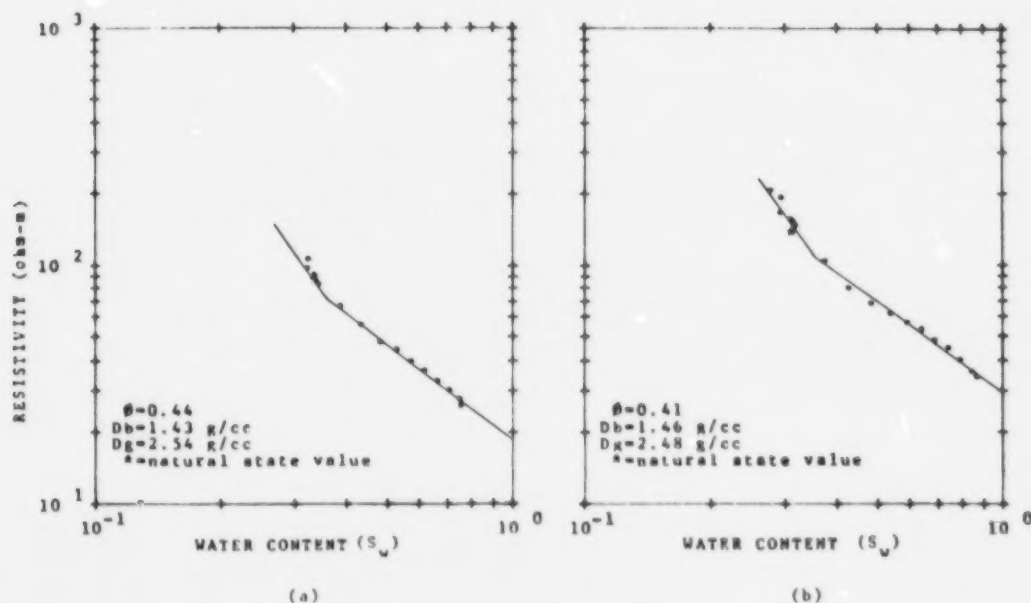


Figure 51.12. Resistivity as a function of water content for samples of alluvium (after Carroll and Muller 1973).

maintains the applicability of Archie's Law to fresh-water environments.

Laboratory data demonstrate the applicability of Archie's Law to the study area, but the terms R_{wa} and R_o must be obtained before dry-hole water saturations can be computed. R_o was obtained in the study area from measurements in alluvium below the water table. Combining Archie's Law with the porosity density equation yields:

$$R_o = aR_{wa}\phi^{-m} = aR_{wa}((D_g - D_s)/(D_g - 1))^{-m} \quad (6)$$

or

$$\log(R_o) = \log(aR_{wa})^{-m} \log((D_g - D_s)/(D_g - 1)) \quad (7)$$

Since R_o can be obtained directly from the resistivity log and D_b may be obtained from the density log, a log-log plot of R_o versus ϕ will provide values for "m" and aR_{wa} , assuming a grain density of 2.60 g/cm³. The cross plot for the three holes represented by the geophysical well logs shown in Figure 51.13 is presented in Figure 51.14. A best fit for this data results in the following form for equation 3 :

$$R_o = 5.10\phi^{-1.76} \quad (8)$$

with $aR_{wa} = 5.10$ ohm-m and $m = 1.76$. A cross plot of selected (unaltered welded tuff) core values from Figure 51.6 is shown on Figure 51.15 with a best fit equation of:

$$R_o = 5.25\phi^{-2.41} \quad (9)$$

with $aR_{wa} = 5.25$ ohm-m and $m = 2.41$. Little significance can be attributed to the close agreement between aR_{wa} from (8) and (9), because the latter were saturated with tap water to measure R_o . However, differences in the cementation exponent, m , can be attributed to changes in cementation, or in this case welding, of the rock. The value of 1.76 is for unconsolidated alluvium derived from volcanic tuffs, and the value of 2.41 is for welded tuff. This difference is comparable to the cementation exponent of sand which ranges from about 1.3 for unconsolidated sand to 2.0 for well-cemented sandstone (Heerst and Nelson 1985).

It must be assumed that the value for m in Archie's Law is equal to the value for n in the saturation equation in order to determine saturation in dry holes. Then, combining these equations through the common R_o term yields:

$$R_o = (aR_{wa}/\phi^m)R_t(S_w)^m \quad (10)$$

Substituting the values for aR_{wa} and m obtained from the density versus resistivity cross plot (Figure 51.14), yields:

$$S_w\phi = (aR_{wa}/R_t)^{1/m} \quad (11)$$

$$S_w\phi = 2.52R_t^{-.568} \quad (12)$$

This equation states that a fractional percent water saturation in the pores of the unsaturated alluvium can be obtained directly from a resistivity log in the dry hole. Using these results, a number of other

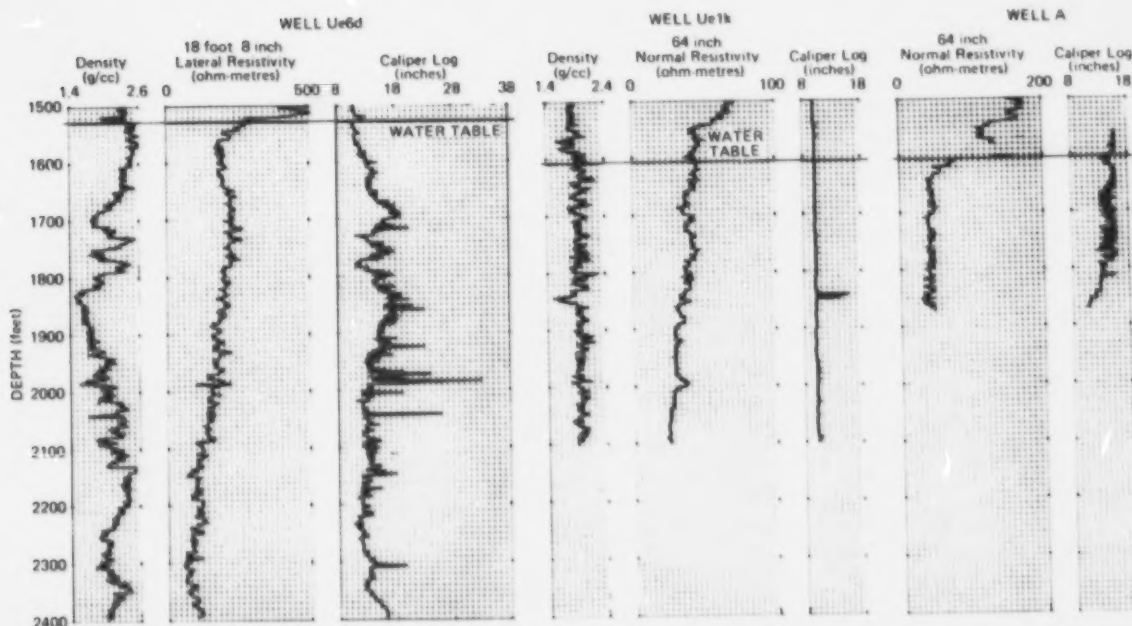


Figure 51.13. Geophysical logs obtained in drillholes Ue6d, UE1k, and well A, which penetrated saturated alluvium (after Carroll and Muller 1973).

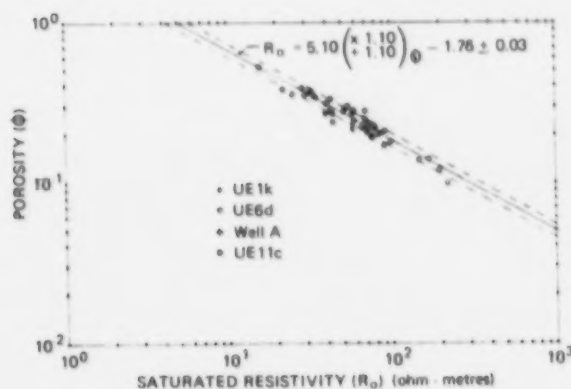


Figure 51.14. Plot of resistivity (R_0) versus porosity (ϕ) in drillholes UE11c, UE1k, UE6d, and well A. All data except those from well A determined directly from density and electric logs in saturated alluvium.

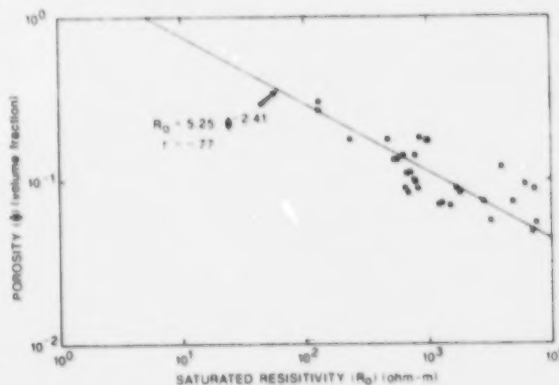


Figure 51.15. Plot of saturated resistivity (R_0) versus porosity (ϕ) for core measurements of unaltered welded tuff (from Anderson 1984).

useful relationships can be determined. The water content by weight can be obtained directly from density log measurements from the following equation:

$$W = (2.52R_1^{-.568})/D_b \quad (13)$$

Also, if a reliable value for the grain density can be obtained, then the porosity can be determined

from the resistivity and density logs using the following equation:

$$D_b = (1 - \phi)D_g + 2.52R_1^{-.568} \quad (14)$$

A comparison of water content measured from core, with water content values from dry-hole resistivity and density logs is presented in Figure 51.16. Resistivity values were obtained with a 64 inch normal array in a mud-filled drillhole. The measurements were corrected for the effect of fluid in the

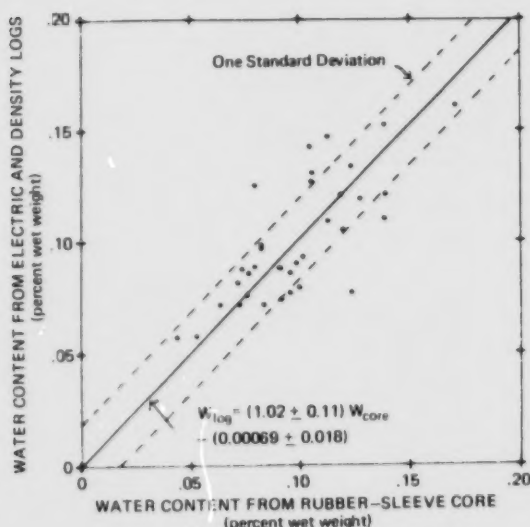


Figure 51.16. Comparison of water content by weight, as predicted from electric and density logs and equation (12), with data derived from core analysis (from Carroll and Muller 1973).

borehole, assuming no invasion of the drilling fluid. Deviations obtained on the plot in Figure 51.16 are probably caused by the large sample size of the probe compared to a number of small samples averaged over the interval investigated by the probe.

Resistivity measurements from a mud-filled hole above the water table must be used judiciously, as Carroll and Muller (1973) have shown. The examples presented in this paper indicate that resistivity measurements from mud-filled holes may be a valid representation of dry-hole resistivities only for arrays having large electrode separations in rocks with low permeability. Further investigations must be conducted to determine the limitations of resistivity measurements in mud-filled holes for a variety of hole conditions. Of course, inductive conductivity measurements are the preferred method for measuring resistivity in a dry hole.

CONCLUSION

Carroll and Muller (1973) showed that porosity and water saturation parameters can be determined for rocks above the water table by applying modified forms of standard mathematical relationships that relate porosity to resistivity and density measurements in a drillhole. Examples presented in this paper also illustrate the complexity of physical proper-

ties above the water table. These complexities make it difficult to measure physical properties above the water table, but they also provide a basis for using physical-property measurements to determine hydrogeological parameters above the water table. The history of water level variations and the associated structural history of a region may be manifested in physical properties that can be measured *in situ*.

Studies of physical properties above the water table may also shed some light on the problem of defining the water table from surface-geophysical measurements. If it is assumed that the water table is a transition zone of decreasing water saturation caused by capillary action above a certain level, then why is this boundary distinctive enough to cause refraction of seismic waves, and reflections from high frequency EM (radar) measurements? Geophysical logs from the study areas show that the water table zone is also a zone of marked compositional changes in the rocks that may ultimately determine geophysical anomalies.

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52. The Use of Electrical Geophysics in Ground Water Exploration and Mapping Ground Water Contamination

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ABSTRACT

During the past decade there has been an increased awareness about the severity of ground water contamination in industrialized areas of the world. While geohydrological studies are fundamentally important in investigating and remediating contamination problems, the integrated use of both hydrologic studies and geophysical studies has proven to be even more effective. This synergistic approach has several practical benefits. First, it results in a better understanding of a particular project than is possible with either hydrology or geophysics alone. Second, the use of passive surface geophysical methods provides a non-invasive means of investigating the subsurface. Third, overall project costs can be significantly reduced by identifying optimum sites for the drilling of monitoring wells, and by reducing the number of wells which have to be drilled.

In addition to contamination problems, important uses of geophysics include exploring for new ground water resources, identifying the extent and quality of existing aquifers, and mapping structure controlling subsurface flow systems.

Several case histories illustrate how various electrical geophysical methods can be used as an integral part of geohydrological studies. The first study illustrates the discovery of a significant and previously unknown ground water resource in Arizona using deep electromagnetic soundings (controlled source audio-magnetotellurics, or CSAMT technique). A second study shows how the underwater self-potential (SP) technique was used to identify leakage locations in the clay liner of a sulphurous waste-pond. Finally, the use of complex resistivity (CR) is illustrated in mapping a plume of contaminants originating from a major industrial site.

53. Geophysical Methods in Groundwater Contamination Studies

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ABSTRACT

Electrical geophysical prospecting methods have been used for decades to detect inorganic contaminants, such as salinity, in groundwater. The higher conductivities of the contaminated pore fluids can provide good targets for the standard resistivity techniques. The past decade, however, has seen a tremendous resurgence of interest in this area of geophysics. In the developed countries, groundwater contamination is now recognized as a serious and entrenched health hazard, and large sums of money are spent on locating and removing the sources of pollution. At the same time, new equipment such as terrain conductivity instruments and ground penetrating radar have dramatically increased the ease and precision with which shallow aquifer contamination can be detected from the surface.

In this paper, we present data for five sites where groundwater contamination either does occur or may soon occur. At Novo Horizonte, São Paulo, a landfill is contaminating a farm well. In Breslau, Ontario, residues from an oil reclamation plant were placed in shallow, unlined lagoons, which have leaked into the groundwater system. At North Bay, Ontario, a major contaminant plume from the municipal landfill discharges into a creek. In Montgomery County, Maryland, and at Camp Borden, Ontario, the task is to monitor changes in groundwater quality with time. In all these cases, we evaluate the role played by exploration geophysics in resolving the hydrogeological problem.

INTRODUCTION

The last decade has seen a significant increase of interest and profitability in the business of exploring for mankind's wastes. Geophysicists, initially perhaps a little reluctant to ply their trade in and around landfills, mine tailings, and effluent lagoons are now starting to play a useful role in the massive waste cleanup and monitoring projects underway in the developed nations. Garbage does not threaten to replace mineral resources as the major employer of

geophysicists, but it provides – and will increasingly provide during the next decade – interesting problems and careers. In an editorial in the monthly magazine of the Society of Exploration Geophysicists, S.H. Ward (1985) wrote regarding the employment outlook for geophysicists:

"The biggest growth area of all, however, is most likely to be in developing groundwater resources and eliminating sources of contamination for groundwater; this area of growth will not be cyclical but will follow population growth."

This statement is remarkable because the modern development of contaminant geophysics has evolved almost entirely outside the established geophysical societies, notably within the journals and conferences sponsored by the National Water Well Association (NWWA). In the NWWA, this small, very user-oriented area of geophysical exploration found an enthusiastic audience. Institutional support has come primarily from the U.S. Environmental Protection Agency, which produced the first comprehensive text on the subject (Benson *et al.* 1983).

In this article, we describe five surveys with which one or more of us has been involved, and which demonstrate the usefulness and some of the limitations of geophysical techniques in locating and monitoring contaminated groundwater. This choice of our own data is admittedly expedient and potentially biasing, but it is a fact that most geophysical surveys performed in the course of contaminant studies are not published. The cases discussed here either are, or soon will be, fully documented elsewhere in readily available journals and proceedings.

GROUNDWATER CONTAMINANT GEOPHYSICS

SCOPE

The term "contaminant geophysics" encompasses a wide range of activities including site selection surveys, contaminant source detection, and the mapping and monitoring of groundwater contaminant plumes.

The general problem, shown schematically in Figure 53.1, arises when the regional groundwater

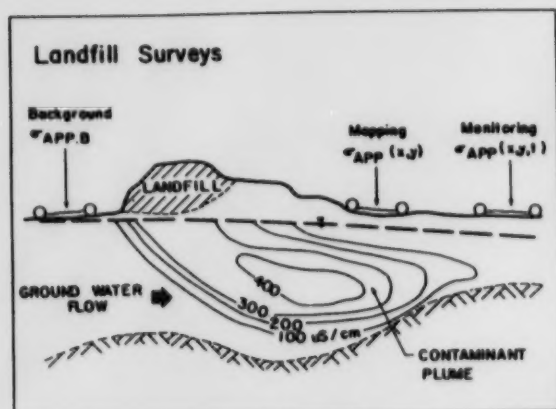


Figure 53.1. Schematic view of a landfill contaminant plume. Surface geophysical monitoring and mapping surveys record the variation in apparent conductivity σ_{APP} , with respect to a background $\sigma_{APP,B}$, in space and time respectively. Subsurface contours of groundwater conductivity depict the advection and dispersion of contaminants by the groundwater flow.

flow regime, perhaps modified by the contaminant source itself (as in mounding of the water tables in landfills), transports pollutants from the source, thereby contaminating an aquifer. The pollutants in question may be organic as well as inorganic; however, it is the inorganics that can raise the conductivity of the groundwater appreciably and give rise to anomalies in apparent conductivities in surface geophysical surveys.

Geophysical exploration for contaminated water is of course nothing new. Saline groundwater was an early target of electrical resistivity methods, and landfill and mine tailing contamination surveys were undertaken in the 1950s and 1960s (e.g. Cartwright *et al.* 1968). Some factors that have combined to establish geophysics firmly in this field are the increased concern about industrial and residential waste disposal practices; and the development, largely by the Canadian manufacturer Geonics Limited, of instruments to measure terrain conductivity using electromagnetic techniques.

EQUIPMENT

The four electrode (galvanic) resistivity methods are still used in contaminant studies but inductive and VLF techniques are now more prevalent. These make use of varying electromagnetic fields to induce current flow in the ground and have the advantages of speed of operation and the ability to penetrate through dry surface materials. The most frequently referenced instruments are the EM31 and the EM34 series produced by Geonics Limited (McNeill 1980). The EM31, with the receiver and transmitter in a single unit, can be operated by one person and has a penetration of roughly 6 m. The EM34 requires two

operators with receiver and transmitter separated by 10, 20, or 40 m cable lengths, giving effective penetrations roughly equal to the spacings. Very Low Frequency (VLF) resistivity instruments, such as are manufactured by Geonics, Scintrex, and EDA, are also used in contaminant surveys. With penetrations usually in the tens of metres and one person operation, they are ideally suited to many problems. All these devices record an apparent admittance or impedance, expressed here as an apparent conductivity, σ_{app} , also referred to below as "response". Ground Penetrating Radar (GPR) has also been used effectively in some instances to image contaminant plumes by virtue of the signal attenuation that high groundwater conductivities produce. An example is given below in the North Bay test case. GPR techniques are described by Benson *et al.* (1983) and some of the many applications by Davis *et al.* (1984) and Vaughan (1986).

DATA COLLECTION AND PROCESSING

Figure 53.2A shows a typical problem. This section is taken near waste lagoons at the Breslube Oil Refinery in southwestern Ontario, a case history discussed later in this paper. Waste chemicals have leaked into the groundwater from surface lagoons to pollute the unconfined aquifer and, possibly, the confined aquifer beneath.

The immediate geophysical target is the contamination level of the unconfined aquifer. Contaminants in the groundwater will increase the response (σ_{app}) of the surface device. That response, however, is also a function of the thicknesses and conductivities of the strata above and below the target. For example, topography will vary the distance between instrument and target. Clay lenses – highly conductive like the contaminated ground – may occur intermittently throughout the area. The measured apparent conductivity therefore is also a function of parameters unrelated to contamination which vary spatially and, in the case of the water table, with time. These parameters constitute the geological noise in the problem; to be successful, the survey must recover the contaminant "signal" from this noise.

MONITORING VERSUS MAPPING

The geophysical problem can generally be classified as one of mapping existing contamination in space, or monitoring contamination with time. In mapping, the goal is a map of the spatial variability of apparent conductivity over a site. Because of the uncertainties raised by the uncontrolled parameters referred to above (clay, topography, etc.), interpreting a mapping survey can be difficult if the response to contamination is not strong. Monitoring, where changes in time are referred to an established background, has the potential for much greater resolution of variations in contaminant levels. Temporal variations in surface moisture, groundwater levels, and surface to-

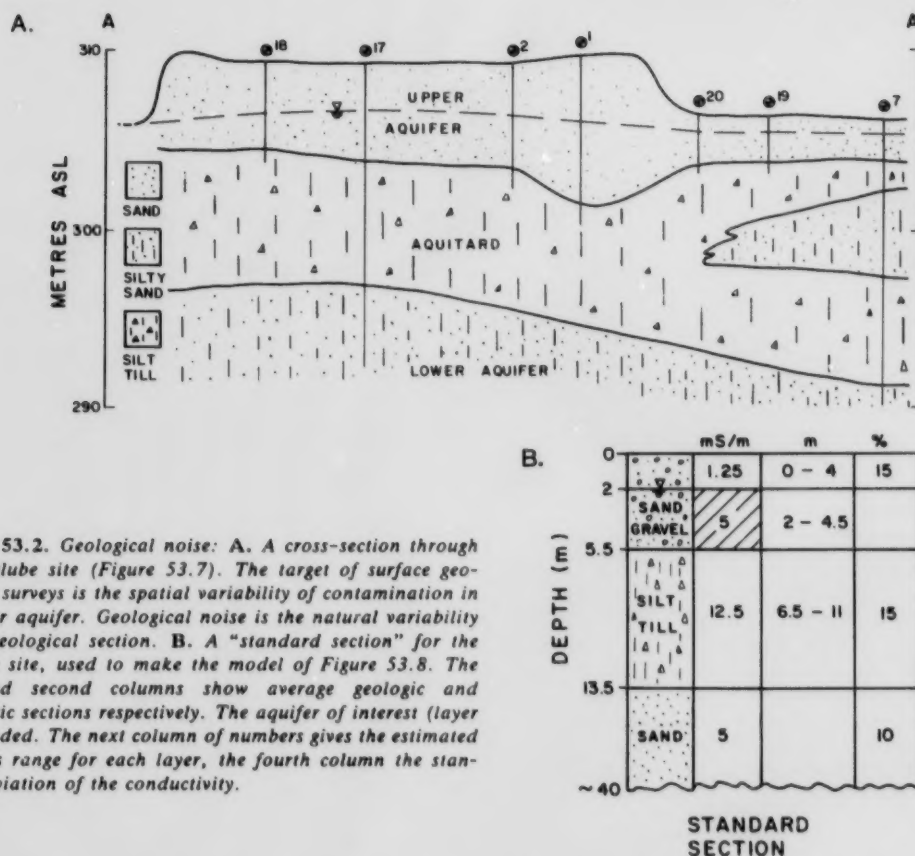


Figure 53.2. Geological noise: A. A cross-section through the Breslube site (Figure 53.7). The target of surface geophysical surveys is the spatial variability of contamination in the upper aquifer. Geological noise is the natural variability of the geological section. B. A "standard section" for the Breslube site, used to make the model of Figure 53.8. The first and second columns show average geologic and geoelectric sections respectively. The aquifer of interest (layer 2) is shaded. The next column of numbers gives the estimated thickness range for each layer, the fourth column the standard deviation of the conductivity.

pography in construction zones are the major sources of noise for monitoring.

SIGNAL FROM NOISE

Contouring

The separation of signal from noise is achieved in large part, as in most geophysical surveys, by the requirement that the contoured anomalies have certain characteristics. Contaminant mapping surveys, carried out with any of several available devices, are usually performed on a grid, and the results contoured. Meaningful anomalies are expected to have a "plume-like" appearance with progressively weakening conductivity levels emanating from a contaminant source. This simple requirement is a powerful discriminator.

Figure 53.3 shows an idealized plume anomaly. In order to compare the anomalies measured with different instruments, and from different surveys, it is helpful to normalize the data by a background response. Because the conductivities tend to rise in an exponential manner as the source is approached, it

is also helpful to use a logarithmic scale so that contours don't cluster around the source. In Figure 53.3 the data are contoured in decibels.

Topography and other lateral variations

In mapping surveys, the effects of surface topography and laterally variable geology are difficult to compensate in any totally satisfactory way. Three-dimensional and even two-dimensional modeling is impractical even where it might be computationally possible. Greenhouse and Slaine (1986) have proposed a statistical approach when the approximate range of topographic, geological, and geoelectrical variation across the site can be estimated, but not measured, at each reading. Figure 53.2B shows a so-called "standard section" for the Breslube site, basically an average geological and a geoelectrical section based on available data. To mimic the spatial variability, one-dimensional modeling of the response for random variation of the parameters is undertaken. One-dimensional algorithms are readily available for these computations, and this approach also allows some prediction of water quality to be made from the geophysical response. The layer

PLOTTING FIELD DATA

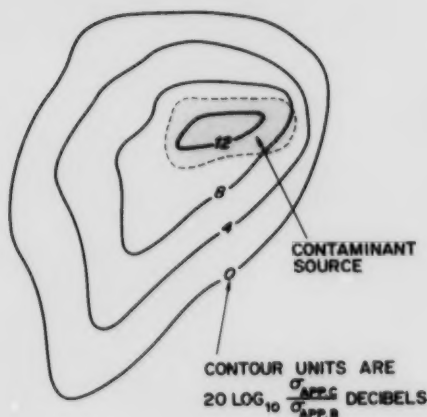


Figure 53.3. Schematic contours of anomalous conductivity about a contaminant source. The raw data $\sigma_{APP.C}$ are normalized by the background and converted to decibel units. Logarithmic units prevent contour clustering around the contaminant source; decibels give convenient whole numbers.

thicknesses are allowed to vary randomly, with a uniform distribution, between the limits shown in the third column. The conductivities of the layers vary normally about the posted mean with a standard deviation given in the rightmost column. An example of the results of this modeling for a VLF resistivity survey, and an analysis of its usefulness, is discussed below in the Breslube case history.

A second approach that appears to work well in those cases where the station topography has been measured is described by Monier-Williams *et al.* (in preparation). A curve drawn at the base of the cloud of points produced in a plot of conductivity versus station elevation appears (on the basis of the few sites where it has been tried), to give a viable estimate of the variation of the normalizing background conductivity as a function of topography. This approach is illustrated in the Novo Horizonté case history which follows.

CASE HISTORIES

THE MUNICIPAL LANDFILL, NOVO HORIZONTÉ, SÃO PAULO STATE, BRAZIL

The landfill serves the town of Novo Horizonté, population about 25 000, a centre for farming and sugar refining, located 485 km northwest of the city of São Paulo. The landfill has been in operation for about five years, and appears to be well managed.

Figure 53.4 is a map of the area surveyed. The ground slopes east away from the landfill towards a

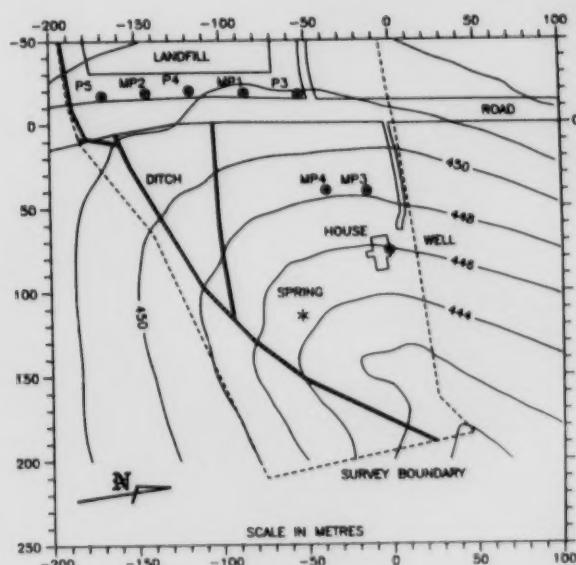


Figure 53.4. Site map for the landfill and adjacent farm at Novo Horizonté, Brazil. Contours, giving elevation above sea level in metres, are based on survey data within the dashed outline and estimates by the authors elsewhere. Circles with crosshairs are sampling boreholes and/or wells. Heavy lines show drainage ditches emplaced to divert contaminants from the well. A small stream runs from the spring to the swamp at the bottom right of the property.

small farm which produces coffee, sugar, corn, and fruit. The farmhouse well is contaminated; the landfill operation is obviously suspect but there is no obvious surface drainage between landfill and well. Geophysical surveys to detect a subsurface connection have been undertaken by personnel from the University of São Paulo (USP) and the University of Waterloo (UW) as part of a cooperative research program funded by the International Development Research Corporation to confirm or disprove the link. This work is described in more detail by Monier-Williams (in preparation).

The farm is on the Bauru Formation, a sandstone interspersed with shales. A weathered zone may extend to a depth of 10 m or more. Background conductivities with the EM34/10H (EM34 with coil axes horizontal and spaced by 10 m) are about 5.0 mS/M.

Figure 53.5A shows the contoured apparent conductivities (in decibels with respect to background) as measured with the EM34/10H. The stations are laid out on a fairly regular grid. The data show a fairly weak anomaly which appears to link the landfill to the farmhouse. The maximum anomaly measured in the farm is 8 db, slightly more than twice background. The contours do not mimic the surface drainage, but rather angle across the topographic gradient. The anomaly, however, is not

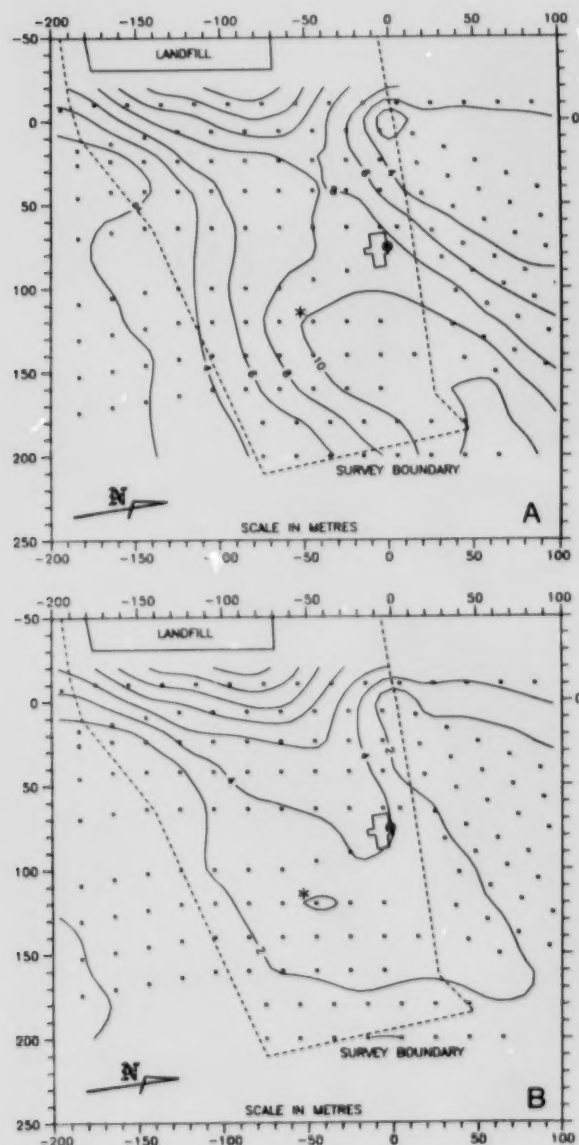


Figure 53.5. Contours of the EM34-10 (horizontal mode) apparent conductivity, normalized by background of 3 mS/M and converted to decibels (db), over the site from Figure 53.4. Zero db represents background. Six db is a factor of 2 above background. Solid dots show points of measurement. The circle with crosshairs is the farmhouse well. A. Raw measurements - the apparent conductivity increases away from the landfill, probably associated with decreasing elevation. B. Measurements adjusted for topography (see Figure 53.6).

strictly plume-like in that it exhibits higher conductivities to the southeast, away from the landfill. This might suggest that the landfill is not the sole source

of the anomaly or, more likely, that topography is influencing the response.

As described in the section above, the topographic effect can often be subdued by redefining the background as a function of topography. Using the topographic control available, the distribution of $\log \sigma_{app}$ is plotted against elevation in Figure 53.6. A line along the well-defined lower edge of the resulting cloud of points is used to define background, and these background values used to renormalize the data and produce the corrected contour map of Figure 53.5B. Now there is a convincing plume-like anomaly linking the landfill and the house. Note that the conductivity contrasts are still very low; only a factor of 1.4 (3 db) exists at the well. This geophysical evidence, of course, is not of itself a proof of contamination cause and effect. The data must be backed up by groundwater sampling. At this site, groundwater monitoring boreholes (Figure 53.4) have further confirmed that the conductivity plume is associated with contamination and the geophysical map therefore becomes a credible map of the groundwater quality. The cost of the geophysical survey, when compared to a drilling program of similar extent, is very low. Its usefulness is as a guide to further hydrogeological studies of the problem.

BRESLUBE REFINERY

The Breslube plant in Breslau, Ontario, operates an oil reclamation business. For 15 years, ending in 1975, it deposited acidic sludge from the reclamation process in unlined lagoons in glacial overburden behind the plant. The pits have since been emptied, but the groundwater pollution will take much longer to reduce to acceptable levels. In 1981, as part of a site cleanup, an inductive resistivity survey was run

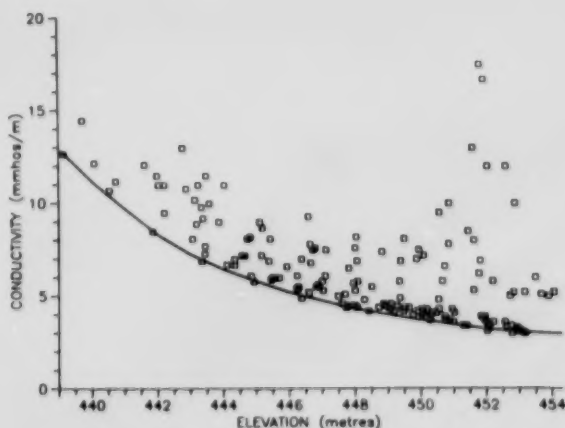


Figure 53.6. Apparent conductivity (EM34-10H) plotted against station elevation for the Novo Horizonte site. The smooth curve drawn through the base of the cloud is taken as an estimate of the background variation with elevation and used to correct the raw data for topography (Figure 53.5B).

to locate the contaminated water (Greenhouse and Slaine 1983, 1986).

Figure 53.7A shows a map of the site. Figure 53.7B shows the VLF apparent conductivity contoured over the site. We expected that the regional groundwater gradients would move contaminants to the southwest towards a major river; however, the conductivity anomaly clearly extends south from the lagoons. Sampling at the borehole locations shown in Figure 53.7A confirm that the groundwater contamination also follows this route. The area surveyed lies in a worked gravel pit, with very irregular topography. A section along A-A' of Figure 53.7A has been given in Figure 53.2A. A topographic survey was available, but it was not possible to locate the geophysical stations accurately enough to attempt a topographic correction to the background as shown in the previous example. Fortunately, the penetration of the VLF is such that the surface topography has apparently not distorted the geophysical plume.

It is important to obtain some idea of the relationship between the geophysical response and the groundwater conductivity (taken as a measure of contamination levels). Accordingly, the stochastic modeling approach outlined above was used with the standard section of Figure 53.2B. The results are shown in Figure 53.8, where the normalized response ($\sigma_{app}/\sigma_{app,b}$) for the VLF is plotted against

the normalized conductivity ($\sigma_1/\sigma_{1,b}$) of the target formation. The solid curve represents the response for the average structure of Figure 53.2B. The shaded envelope encloses the response curves of 20 random models about the standard section, representing (in a loose way) the 95 percent confidence limits of the response. We see, for example, that for no contamination (at the intersection of the envelope with the horizontal axis) variability in the response of about 30 percent (2 db) is predicted.

How do the groundwater monitor data confirm this model of the response? In Figure 53.8 the VLF response beside each borehole is plotted against the maximum groundwater conductivity measured in the borehole within the shallow aquifer. Both the response and the water conductivity are normalized by an appropriate background value.

The result is not immediately encouraging. The data points lie well above the prediction envelope. A number of excuses can be made but the VLF misfit emphasizes a basic weakness in the process of comparison – the choice of background. If the response background were lowered, say by a factor of 2 (6 db), the well data would agree more closely with the model envelope, though still showing more scatter than predicted. The problem of background choice aside, the comparison assumes that; a) water conductivity is linearly related to the formation conductivity, and more importantly; b) that the

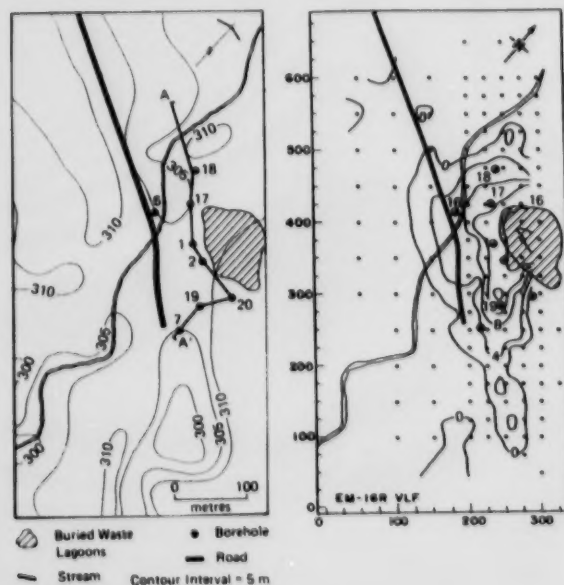


Figure 53.7. The Breslau site, Breslau, Ontario. A. The site, showing (smoothed) elevations and sampling borehole locations. The section A-A' is given in Figure 53.2. The waste lagoons are hatched. B. Contours of EM-16R (VLF) conductivity over the site, in units of decibels. Background is 7 mS/M. Solid dots indicate points of measurement.

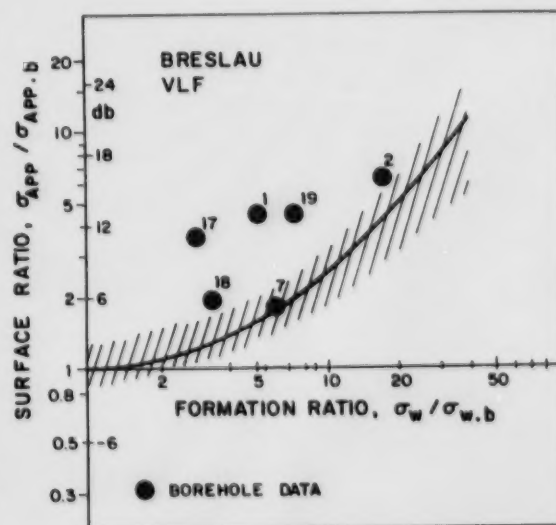


Figure 53.8. Observed versus predicted response, the Breslau site. The solid curve shows the predicted VLF response (apparent conductivity normalized by background) for the section in Figure 53.2B as a function of normalized conductivity of the second layer (target aquifer). The solid circles show the measured response at the test wells of Figure 53.7 plotted against the maximum groundwater conductivity measured in the well, both quantities normalized to assumed background.

borehole sample is representative of the volume contributing to the response of the VLF unit. It is probably significant that a similar comparison of EM31 data with the borehole conductivities provided a much better fit (Greenhouse and Slaine 1986). The zone of influence for the EM31 is much smaller than the VLF's, and may therefore be better represented by the borehole readings.

We conclude that the one-dimensional stochastic models may be a useful guide both to the choice of instrument to be used at a particular site, and to the general relationship (and uncertainty therein) linking surface geophysics and groundwater conductivity. They cannot, in general, simulate the complexity of the subsurface sufficiently well to link quantitatively surface and groundwater conductivities.

NORTH BAY

This northern Ontario city has a landfill with a well-developed contaminant plume. The plume flows through glaciolacustrine sands that overlie irregular Precambrian bedrock. The route follows a bedrock depression to a discharge area some 800 m from the landfill perimeter. A VLF map of the plume is shown in Figure 53.9A and a more detailed map of the EM31 contours in Figure 53.9B. The sands, saturated with natural groundwater, have a fairly uniform conductivity of 2.5 mS/M. Used as a background conductivity in both maps, the 0 db contour effectively separates the plume (positive contour levels) from the bedrock topography influences (Ben Miloud 1986).

The groundwater movement in the area has been extensively studied (Hewetson and Cherry 1981; Moore 1986). As part of these studies, several Ground Penetrating Radar traverses were measured by personnel from A-Cubed Incorporated using their pulse EKKO® system transmitting 10 ns pulses. The radar work was described by Cosgrave *et al.* (1987a, 1987b). Figure 53.10 compares the GPR data along the transect A-A' in Figure 53.9B with groundwater conductivities measured with multilevel piezometers by Moore (1986). Note the coincidence of the attenuation of the radar signals and high groundwater conductivities on the other. The radar signals are almost completely blanked below the 100 to 125 mS/M contour. The result is a negative image of the upper surface of the plume, giving considerably more detail of its vertical structure than is available from the inductive resistivity surveys. Cosgrave *et al.* (1987b) also presented GPR transects of this plume taken one year apart, which showed significant differences in their attenuation patterns related to movement of the plume.

In this particular environment, where background formation conductivities are low, GPR provides an excellent means of both mapping and monitoring the plume. Radar equipment and data proc-

essing are still expensive compared to inductive resistivity and the penetration is generally lower. The appropriate conditions for successful use in contaminant studies must be well understood.

There are very few published case histories available for geophysical contaminant monitoring. Here, we review two that demonstrate the possibilities of the techniques, and at two extremes of scale.

THE CAMP BORDEN INJECTION EXPERIMENT

In 1982, 12 000 litres of contaminated water, containing 918 mg/L of chloride and 323 mg/L of bromide in addition to a variety of organic and heavy metal tracers, were injected into an unconfined sandy aquifer on the Canadian Forces Base at Camp Borden, Ontario. The slug was monitored for almost two years by a dense array of multilevel sampling boreholes (Mackay *et al.* 1986). As part of this monitoring effort, geoelectrical surveys were conducted for eight months following the injection (Faulkner 1983; Greenhouse *et al.* 1985b). The area surveyed, depicted in Figure 53.11, was about 1500 m². The slug initially covered an area (as defined by anomalous chloride levels) of about 20 m², and was concentrated between depths of 2 and 3.6 m below ground surface. After 4.5 months, the plume centre moved roughly 25 m, and the area expanded to 80 m².

There was no compelling hydrogeological need for a geophysical monitor, but the situation offered a unique opportunity to examine, on a small scale, the sensitivity of surface geophysics to a known contaminant distribution. Background readings were made over the site prior to the injection with both an EM31, and a collinear dipole-dipole sounding array. The measurements were made at 2 m intervals across the slug's path, on lines spaced by 2 m. The 2 m dipoles were separated by 2 (n=1) to 12 (n=6) metres. Background conductivities along individual lines varied less than 10 percent from their mean, which ranged from 5 mS/M for the shallow dipoles to 7 mS/M for the deeper penetrating geometries. The background values at each point of measurement were used to normalize the later readings, and the percentage variation $100 (\sigma_{app} - \sigma_{app,b}) / \sigma_{app,b}$ contoured.

The EM31 measurements showed no discernible anomaly, even immediately following the injection. The dipole readings, however, were able to follow the plume for the 239 day period over which measurements were made. Figure 53.12 shows the contoured anomaly data for the 34th day following injection. These data are compared to the geochemical data obtained from multilevel sampling piezometers 29 days following injection, the sampling closest in time to the geophysical measurements, in plan (Figure 53.12A), and section (Figure 53.12B). The plan contours in Figure 53.12A are for a 2 m electrode separation with dipole separation of 6 m (n=3). The hachures fill the 50 mg/L

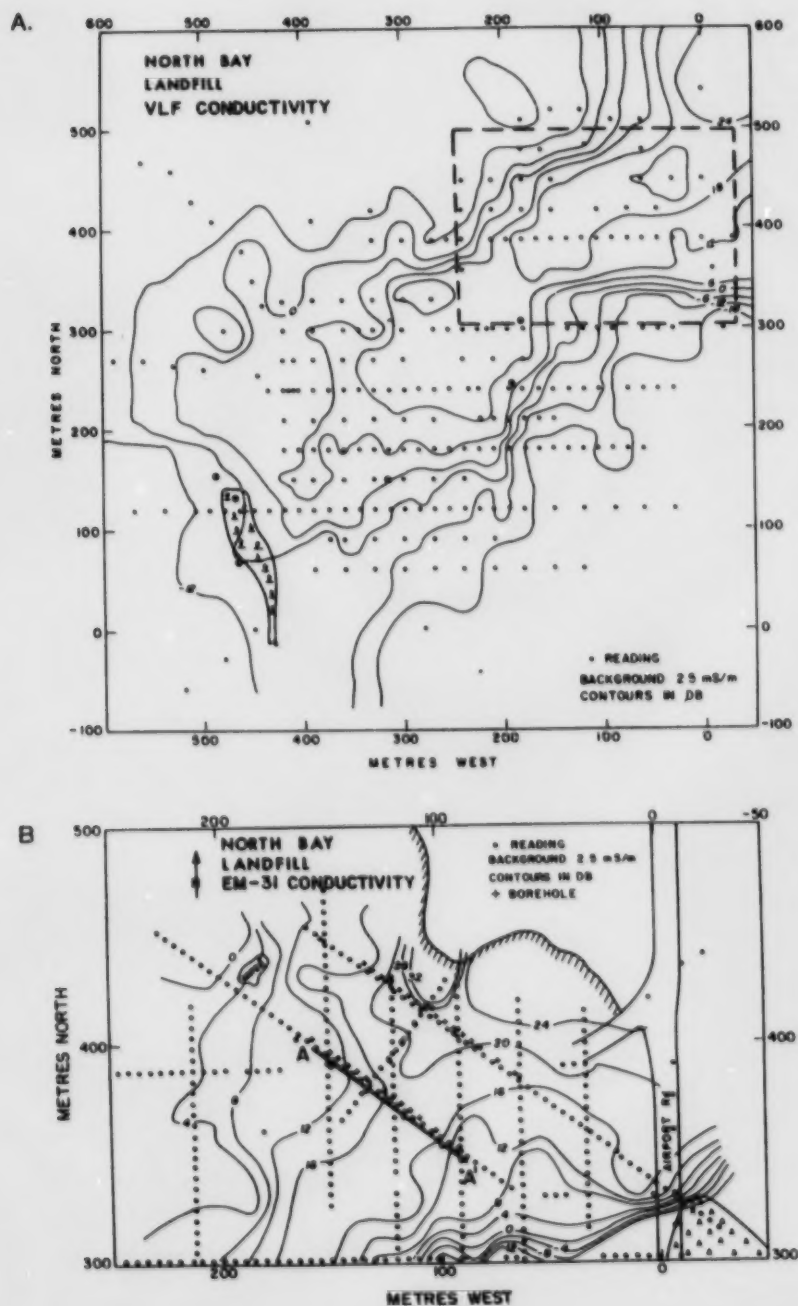


Figure 53.9. A contaminant plume at the North Bay landfill. Contours are in decibels, referred to a background of 2.5 mS/M. Positive contours represent contaminated groundwater, negative contours show the influence of shallow bedrock. A. The VLF conductivity plume observed at the North Bay landfill site. The landfill itself is just beyond the northeast corner of the map boundary. Leachate from the landfill discharges in the swamp area to the southwest. B. The EM-31 conductivity plume within the dashed square in the upper right of Figure 53.9A. Ground penetrating radar data along the traverse A-A' are shown in Figure 53.10.

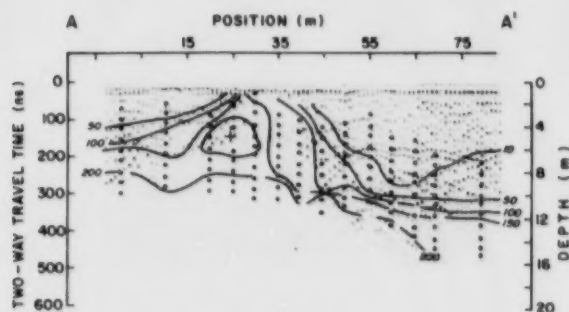


Figure 53.10. A comparison of GPR and multilevel borehole sampling data along section A-A' of Figure 53.9A, across the North Bay plume. The contours are of groundwater conductivity in mS/M, and they are superimposed over the 100 MHz radar traces recorded every metre along the traverse. Solid dots indicate the multilevel ports. The attenuation of the radar returns over the plume coincide well with the high water conductivities in the boreholes.

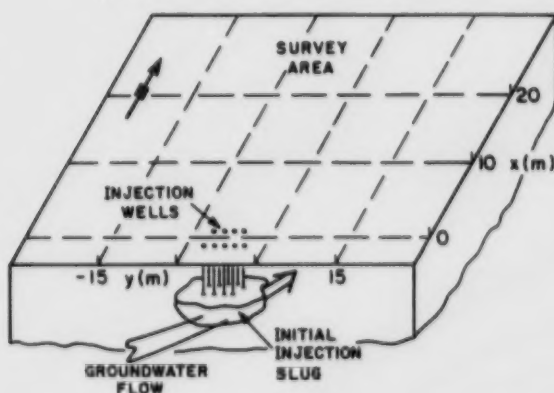


Figure 53.11. Diagram of the Borden injection site and monitoring grid. The grid is measured north (down gradient) and east from the centre of the 9 well injection. The injection depth varied between 2 and 3.6 m below ground surface.

chloride contour defining the slug; 300 mg/L levels where recorded at its centre. The conductivity anomaly attains 30 percent above background and, although smeared out by the electrode spacing used, it clearly outlines the anomalous chlorides. Figure 53.12B shows a pseudo section measured along a line 6 m north of the injection, and this is compared in the lower part of the diagram with a two-and-one-half-dimensional model computed by Dr. Joe Wong of Jodex Limited, Toronto. The model slug is based on the outline of the 50 mg/L chloride contour. The model anomaly roughly matches the data but fails to predict the central low found for the larger dipole spacings. The probable reason is that the model slug is wider than the one seen by the

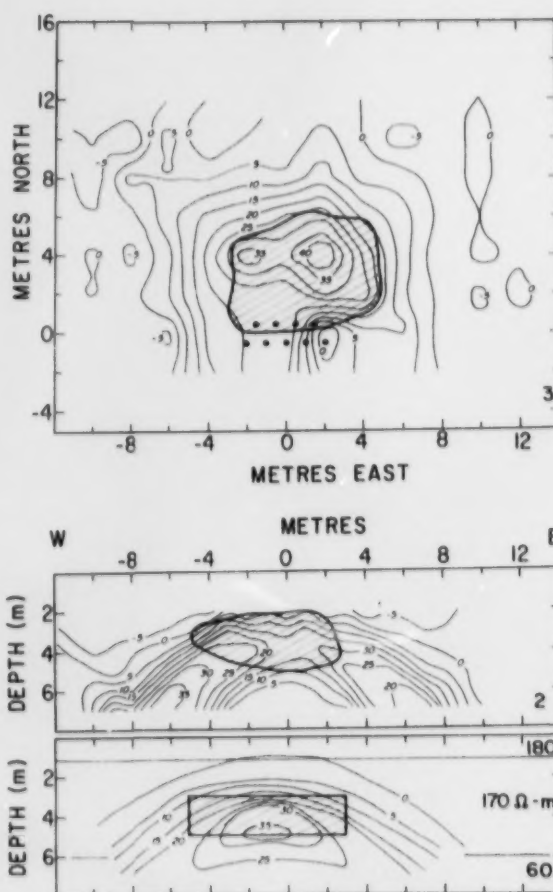


Figure 53.12. Dipole-dipole response over the survey grid, on the 34th day following injection, at the Borden site. The hachures fill the 50 mg/L chloride contour (considered the anomalous minimum) as constructed on the 29th day from sampling borehole data. The contours give percentage increase of the measured apparent conductivity over the background (pre-injection) levels. A. Plan view, constructed with two metre electrode separation with collinear dipoles separated by 6 m ($n=3$). B. Cross-section along Line 6 north. Measured pseudo section (upper diagram) is compared to a model (lower diagram) of the slug response to the collinear dipole array. The modeled slug is set in a three layer earth with resistivities as shown. Model responses computed by Dr. Joe Wong, Jodex Limited. Differences between modeled and measured responses probably reflect the fact that slug conductivities are high near the centre (not uniformly distributed as modeled) and the effective target therefore smaller than modeled.

dipole sounding, and that the effective target for the electrical surveys is actually bounded by higher chloride levels than the 50 mg/L used here.

The survey showed that in this environment, simple geophysical surveys could track the plume. Reading errors were less than 3 percent, and anom-

ally levels only 10 percent above the background were reliably detected. The usefulness of these types of monitoring surveys is obviously limited to detailed experimental hydrogeological investigations.

THE OAKS LANDFILL, MONTGOMERY COUNTY, MARYLAND

In this final case history, we look at monitoring applications on a larger scale. One of the most interesting developments in groundwater geophysics involves this municipal landfill north of Washington, D.C. The Oaks is a 32 ha site surrounded by a 9 m berm. It was constructed in 1981 and began operation in June of 1982. It was designed as an attenuation-type landfill that would allow a limited amount of leachate to infiltrate into the groundwater below. Monitoring wells were installed around the site during construction, but various legal actions brought by homeowners and citizens groups in the area prompted a review of the whole monitoring process. From that review came the recommendation that a geophysical monitor be installed. Geotrans Incorporated, a groundwater consulting firm in Virginia, installed a geophysical monitor around the 4 km boundary of the site in 1986. Rumbaugh *et al.* (1987) have reported the details and results of the initial readings. The site is set on weathered crystalline rock (saprolite) that ranges from soil with no residual structure to a friable rock that, undisturbed, retains some signs of its original structure. Porosity may be as high as 30 percent, and electrical conductivity is typically 2.5 mS/M. A site map is shown in Figure 53.13. Depth to unweathered bedrock around the perimeter varies from 2 to 30 m.

The landfill had been in use for about four years prior to the installation of the geophysical monitor. The perimeter is also monitored by 15 test wells at roughly equal intervals. The geophysical monitor was installed to complement these point samples by checking the average electrical properties of the subsurface between boreholes. Geotrans Incorporated has located 282 geophysical monitoring points at which it makes bimonthly readings with the EM34, using 10 and 20 m coil spacings. In addition, 15 Wenner resistivity soundings are repeated at the same time interval. The monitoring frequency and methodology was to be reviewed following the first year of operation. Geotrans has also studied the effects of rainfall, proximity to fences, and a nearby microwave relay station on the geoelectric readings.

Figure 53.14, redrawn from Rumbaugh *et al.* (1987) gives an example of the repeatability of the 20 m EM34 readings along a 1 km section of the perimeter traverse. The three sets of readings were recorded at 3 month intervals. The data are assumed to be independent estimates of background. The last two traverses were each recorded following a period of heavy rainfall, which is thought to account for the increase in conductivity compared to the first trav-

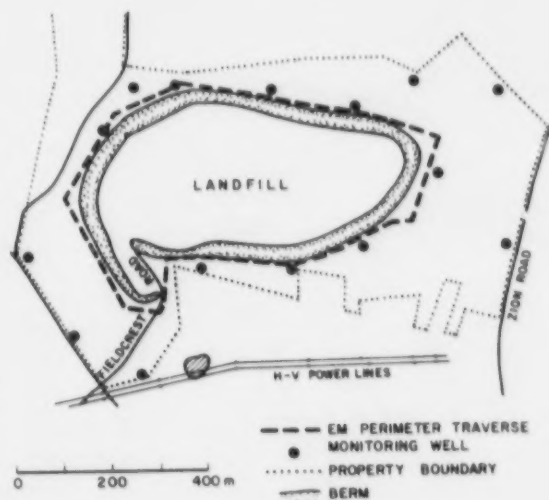


Figure 53.13. Diagram of the Oaks landfill, Montgomery County, Maryland (redrawn from Rumbaugh *et al.* (1987)), showing the perimeter traverse followed by the geophysical monitor.

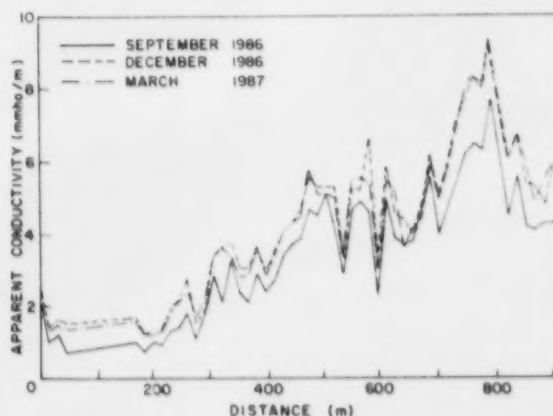


Figure 53.14. Successive EM34-20V measurements along a 1 km stretch of the Oaks landfill perimeter (redrawn from Rumbaugh *et al.* (1987)).

erse. This increase is remarkably constant on a linear scale across the traverse, but it amounts to almost a 100 percent increase for the low conductivity readings at the left of the diagram. This level of background noise will have to be taken into account when describing the resolution of the geophysical monitor.

It will be some time before the effectiveness of the Montgomery County Landfill geophysical monitor can be evaluated. Indeed, the attenuation liner may keep contaminant levels close to background and the monitor never show a significant response.

In an article based on a hypothetical geophysical monitor similar to the Oaks site, Greenhouse and Monier-Williams (1985a) pointed out what they felt were important considerations in any design. Firstly, the cost-effectiveness of the geophysical monitor will always be measured against the cost of additional monitoring wells. Perhaps unjustly, point samples are always considered more authoritative than the volume averages produced by electrical methods. Secondly, change is inevitable. Improved equipment will be marketed, and the environment (topography, drainage, fences, power lines, etc.) of the site will probably be altered over the lifetime of the monitor. The installation must therefore be easily adaptable, and expensive permanent installations should be avoided.

Thirdly, limits to detection must be established. While the monitor may never be triggered, it is important to know what contamination could pass undetected. Numerical modeling is the key to this. It requires that the contractor and client agree on certain scenarios of leakage to be modeled, and that the responses for those scenarios be thoroughly explored.

The background levels against which anomalies are to be measured must be thoroughly understood. The noise in the system stems from errors in reading and calibrating the measuring equipment; the variable inputs of cultural sources such as fences, powerlines, and transmitters; and from natural variations in the bulk conductivity of the ground. This background, and the statistics of its variability, should be determined in advance of the introduction of contaminants to the site. Redundancy, the application of more than one device to the task, is essential in the early stages of the monitor. As the numerical models are at best crude approximations of reality, weak anomalies should be corroborated independently whenever possible. Finally this corroboration must include borehole sampling data as well as other geophysical techniques.

SUMMARY

This paper has reviewed a decade of our experience in the application of geophysics to groundwater contamination problems. It will be interesting to see, but difficult to predict, what the next decade will hold for this subdiscipline. The market for solutions to the growing problems of groundwater contamination will probably expand rapidly. The role that geophysics will play in this market is not so clear. Managers of petroleum and mineral exploration projects are well aware of the benefits of geophysics, and are usually trained in its use. By contrast, the managers of waste storage and cleanup operations, environmentalists, chemists, civil engineers, etc., usually are not. It is also the case that some of the work in these poorly regulated, fringe areas of the discipline is un-

dertaken by unqualified personnel, individuals who can operate the equipment but are not trained in the proper interpretation of the data. This can give rise to unjustified expectations on the part of the client. Geophysical education in the universities and professional organizations where hydrogeologists and waste managers are trained seems the best solution. The National Water Well Association, through its short course program, has been particularly effective in this regard. One of the real challenges facing geophysics is to detect (non-conducting) organics on - or beneath - the water table. Some progress on this has been claimed (Saunders and Cox 1987; Olhoeft 1986), but the topic remains controversial.

There is a need for more research in methodology and equipment, and for more competition in the market for inductive resistivity equipment. There is a particular need for all-in-one, multi-frequency terrain conductivity devices that can profile at several penetration levels simultaneously.

Doing geophysics in and around waste is usually unpleasant and sometimes unhealthy. Still, exploration geophysicists might be wise to accord waste heaps some of the respect they give bright spots and crossover anomalies. As the movie prospector says, "there's gold in them thar hills"!

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54. Advances in Electromagnetic Methods for Groundwater Studies

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ABSTRACT

In the past decade, both inductive electromagnetic survey instrumentation and associated interpretive techniques have become refined to the point that electromagnetic techniques are now widely used for geological mapping as well as for the direct detection of conductive orebodies. Electromagnetic survey techniques have been particularly successful in exploration for potable groundwater, for mapping industrial contaminants in groundwater, for measuring salinity levels in aquifers and monitoring coastal saline intrusion, and for mapping soil salinity in connection with crop growth.

Regardless of the technique employed, it is the terrain conductivity that is measured, and it is a particular advantage of electromagnetic techniques that small variations in conductivity can often be detected. A further advantage is that most electromagnetic techniques allow measurement to be made rapidly, and survey costs are generally less than those associated with conventional DC resistivity surveys or, conversely, larger areas can be surveyed in greater detail for comparable cost. A disadvantage of electromagnetic instrumentation is that although the shallower units cost about the same as resistivity equipment, the deeper penetration systems are relatively expensive. In general, electromagnetic systems are most effective in looking for the better conductors and are ineffective in searching for resistive material. Furthermore, in some cases, interpretive techniques are still under development and in all cases some knowledge of electromagnetic theory is desirable for a successful interpretation.

To date, the most successful electromagnetic techniques have been dipole/dipole systems of the slingram and ground conductivity meter type, large-loop time-domain systems, VLF plane wave (and to a lesser extent CSAMT) systems. This paper briefly summarizes the advantages and disadvantages of each technique using several case histories to illustrate different features of each approach. In several cases, two different electromagnetic techniques have been used at the same measurement site, facilitating an interesting comparison.

INTRODUCTION

Measurement of the electrical resistivity of the earth has been a tool for groundwater exploration for

many years (Zohdy *et al.* 1974). In the past, such measurements were carried out using arrays of grounded electrodes (Wenner, Schlumberger, dipole-dipole, etc.) to inject current into the ground and to measure the resulting potential difference. While often successful, the use of grounded electrodes can encounter problems in areas of high surface resistivity, where obtaining sufficient current flow can be difficult. Furthermore, considerable effort is usually required to lay out the array so that resistivity surveys tend to be expensive to perform. For these and other reasons discussed later, there is growing interest in the use of non-contacting electromagnetic (EM) techniques to measure terrain resistivity. In some cases, reconnaissance EM surveys are now used to locate anomalous areas to be detailed using conventional resistivity techniques. In other cases, both EM and conventional resistivity techniques are used together, employing joint inversion to help overcome the problems of equivalence associated with either technique when used alone, and in an increasing number of cases an EM survey will be the main "electrical" tool used to resolve a groundwater problem.

After a brief review of the factors controlling the electrical resistivity/conductivity of metallic mineral-free rocks and soils, this paper will discuss application of electromagnetic techniques to four groundwater problems:

1. Groundwater exploration
2. Groundwater contamination detection and mapping
3. Saline intrusion mapping
4. Soil salinity mapping

Major emphasis will be on groundwater exploration, for which case histories from both tropical and temperate regions will be presented. For the other three applications, brief summaries of the uses of electromagnetic techniques will be given with one or two case histories to depict the state-of-the-art.

We will restrict our attention to ground measurements. Although there is increasing interest in airborne measurement of electrical conductivity for mapping geology with some excellent case histories (Palacky 1986), those applications where airborne electromagnetic techniques can be used effectively are still unclear; the superior spatial resolution that can be achieved with ground instrumentation is usually required at this stage of problem definition.

FACTORS AFFECTING TERRAIN CONDUCTIVITY

In most groundwater studies, it can be assumed that the soil and rock matrix does not contain conductive metallic minerals, and electric current flow therefore takes place through the soil water (Figure 54.1). Under this condition, major factors affecting the electrical conductivity (reciprocal of resistivity) of the bulk soil or rock are:

1. porosity
2. conductivity of included soil moisture
3. shape of soil/rock pore spaces
4. degree of saturation (fraction of pore space actually filled with moisture)
5. temperature
6. presence of clays with moderate to high cation exchange capacity (CEC)

For a completely saturated soil, the influence of the first three factors is described by Archie's Law, which is satisfactorily accurate for unconsolidated as well as lithified materials (Jackson *et al.* 1978). Thus:

$$\sigma_a = \sigma_w n^m \quad (1)$$

where

- σ_a = bulk conductivity of soil (S/m)
- σ_w = conductivity of soil water (S/m)
- n = soil porosity (volume of soil moisture divided by total sample volume)
- m = a factor which varies with particle shape from 1.2 for spheres to 1.9 for platy fragments.

The conductivity of soil water σ_w is given (for dilute concentrations of electrolyte) by

$$\sigma_w = 96500 \sum C_i M_i \quad (2)$$

where

C_i = number of gram equivalent weights of i^{th} ion per m^3 of water

M_i = ionic mobility of the i^{th} ion (m^2/secV)

In the event that the soil is partially desaturated, soil conductivity varies approximately as (Keller and Frischknecht 1970)

$$\sigma_d = \sigma_a s^k \quad (3)$$

where

σ_d = conductivity of partially saturated soil

s = fraction of total pore volume filled with electrolyte

k = a factor experimentally determined to be approximately two

The temperature dependence of the conductivity of the bulk soil sample is determined (at temperatures above freezing) by the temperature dependence of the ionic mobility, which is of the order of 2 percent per degree Celsius for common ions.

The presence of clays is often considered (Keller and Frischknecht 1970) to simply add an additional component to the electrical conductivity which is a function of clay content and type (CEC), and is essentially independent of the ionic component described by equation (1). The significance of the clay contribution is clearly largest when the concentration of ionic conductors is low and conversely often becomes negligible at high ionic concentration, especially for clays of low to moderate CEC.

Throughout this paper the use of conductivity over resistivity will be preferred, principally since, as equations (1) and (2) imply, a given increase in the number of ions in soil water, such as may occur in groundwater contamination, increases soil conductivity by the same amount regardless of background conductivity, whereas the reduction in resistivity from the increase in number of ions is strongly affected by the number of ions already present. We will express conductivity in mS/m since in these units conductivity of most terrain materials falls within the range 1 to 1000 mS/m . In groundwater contamination studies, the specific conductance of soil water in $\mu\text{S/cm}$ is often found. This quantity is divided by 10 to obtain σ_w in mS/m . Resistivities in Ωm are divided into 1000 to obtain conductivity in mS/m , and vice versa.

We often need an approximate relationship between bulk soil conductivity and ionic concentration. A plot of equation (1) for various values of m is shown in Figure 54.2. Representative values of porosity for sedimentary materials are listed in Table 54.1 from which we observe that well sorted coarse material such as sand and gravel generally has lower porosity, 20 to 35 percent, than well sorted fine material for which porosity is 40 to 55 percent; we would therefore expect the bulk conductivity of coarser material to be lower, as is often observed. We also note from the table that a value of porosity

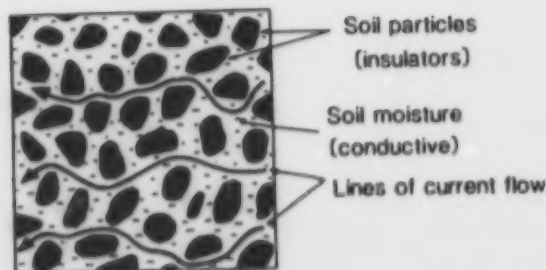


Figure 54.1. Schematic current flow in soil sample.

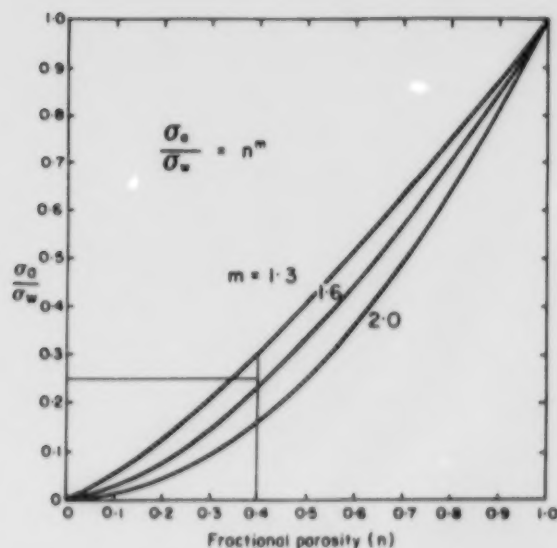


Figure 54.2. Formation factor (n^m) for various values of m .

of about 40 percent might reasonably be taken as average for typical unconsolidated materials, in which case Figure 54.1 shows that, very approximately, $\sigma_o/\sigma_w \approx 0.25$, relatively independent of soil structure (i.e. m). From equation (2), we calculate (the mobilities of Na^+ and Cl^- are 5.2×10^{-8} and $7.9 \times 10^{-8} \text{ m}^2/\text{secV}$, respectively at 25°C), that the conductivity of a solution of 1 g of NaCl in 1 m^3 of water (1 ppm) is 0.22 mS/m, in reasonable agreement with the statement by Todd (1964) that for most natural waters a concentration of 1 ppm of total dissolved solids (TDS) results in conductivity of about 0.16 mS/m. The coincidence between 0.22 mS/m for NaCl and 0.16 mS/m for a natural mixture of ions lies in the fact that ionic mobilities and weights of commonly occurring ions are relatively similar.

TABLE 54.1. REPRESENTATIVE POROSITY RANGES FOR SEDIMENTARY MATERIALS (after Todd 1964).

Material	Porosity %
Soils	50-60
Clay	45-55
Silt	40-50
Medium to coarse mixed sand	35-40
Uniform sand	30-40
Fine to medium mixed sand	30-35
Gravel	30-40
Gravel and sand	20-35
Sandstone	10-20
Shale	1-10
Limestone	1-10

Finally we conclude that, since

$$\sigma_w (\text{mS/m}) \approx 1/6 \times \text{TDS (ppm)}$$

and

$$\sigma_a = 1/4 \times \sigma_w$$

then

$$\sigma_a (\text{mS/m}) \approx 1/25 \times \text{TDS (ppm)}$$

so that addition of approximately 25 ppm of TDS to soil water will increase the saturated bulk soil conductivity by 1 mS/m. The limits on TDS for potable water are often considered to be 500 ppm, in which case our approximate relation yields a saturated bulk conductivity of 20 mS/m, which is about the right value for clay-free soils. We note, however, that this relatively low conductivity can often be exceeded by the contribution from the clay content.

In summary, ground conductivity varies principally with:

1. soil structure (coarser structure and/or smaller porosity producing lower conductivity)
2. clay content (increasing clay fraction, particularly with high CEC) producing higher conductivity
3. soil moisture content (increasing moisture producing higher conductivity)
4. directly with increasing conductivity of included soil moisture

ELECTROMAGNETIC INSTRUMENTS

There are basically three types of electromagnetic instruments now used for groundwater studies. These are:

1. conventional VLF plane-wave instruments including VLF resistivity
2. dipole/dipole frequency-domain instruments, including ground conductivity meters and borehole induction loggers
3. time domain (transient) electromagnetic systems (TDEM)

In this section, we will give a brief description of each, summarizing their advantages and disadvantages for groundwater work.

VLF INSTRUMENTS

One of the earlier electromagnetic techniques, the simple lightweight VLF receiver responds to powerful signals broadcast by VLF transmitters located throughout the world. In the conventional VLF instrument, measurement is made of the magnetic field which, in the absence of subsurface conductors, is horizontal and linearly polarized. Subsurface conductors cause the field to become elliptically polarized and the major axis to tilt with respect to the

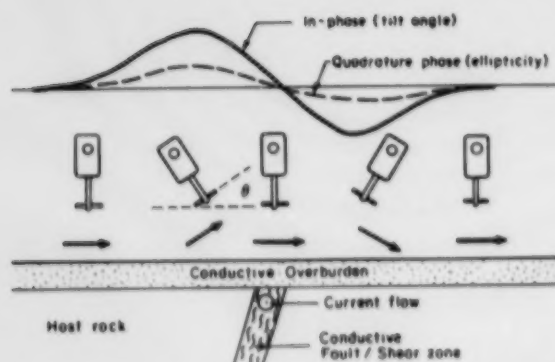


Figure 54.3. VLF response over conductive dike.

horizontal. In passing over a vertical conductor, the tilt angle exhibits crossover behaviour as shown in Figure 54.3. Until recently, it has been assumed that the response from localized conductors was due to induced eddy current flow. However, recent calculations by the author have shown that, except in the most resistive host rock, essentially all response comes from galvanic current flow, also known as current gathering. This means that the influence of the surrounding medium must be taken into account when calculating instrumental response, with the unfortunate consequence that "free-space" calculations are of little use for interpreting field data. Many years ago, Vozoff and Madden (1971) developed a suite of interpretation curves for VLF systems and this data is still the best available. Filtering techniques such as the Fraser filter (Fraser 1969) which converts tilt-angle crossovers into peaks, and the Karous filter (Karous and Hjelt 1983) which calculates the equivalent source current, assumed to be at known depth, are quite valid and often useful for visualization of the sources of the VLF response. However, many experienced users, concerned about losing detail in the filtering process, prefer to make their final interpretation on raw data.

A factor which must be considered with VLF instruments is that they respond most strongly to long targets whose strike direction points within $\pm 45^\circ$ of the direction to the VLF transmitter — and transmitters are not always available in the right direction. In this case, it is possible, but less convenient, to use a small portable VLF transmitter.

The depth of exploration of VLF systems is determined, in the absence of conductive overburden, by the electrical skin depth in the host rock; where conductive overburden exists, it is skin depth in the overburden which is the limiting factor. In either case, the exploration limit is about two-thirds of a skin depth so it is approximately given by

$$D = 2/3 \times \delta = 330 (q/f)^{1/2}$$

TABLE 54.2. VLF EXPLORATION DEPTH.

Resistivity (Ωm)	Depth (m)
10	7
30	13
100	23
300	40
1000	73
3000	127

where

D = approximate exploration depth (m)

δ = skin depth (m)

q = resistivity (Ωm)

f = VLF frequency (Hz)

Since all VLF transmitters operate within the narrow frequency range of 15 to 30 kHz, we have used an average frequency of 20 kHz to calculate the exploration depths given in Table 54.2, from which we see that, in regions where overburden and bedrock are resistive, depths of many tens of metres can be achieved, but in areas where the overburden resistivity is less than 30 Ωm , the depth is of the order of 10 m. It is also clear that if the overburden resistivity or thickness, or bedrock resistivity, varies as we survey along a line, so too will the exploration depth.

The VLF resistivity instrument, on the other hand, measures the local ratio between the horizontal VLF electric and magnetic fields to derive a magnetotelluric apparent resistivity. Measurement is also made of the electrical phase angle between these two field components, which permits detection of an electrically layered earth. Most interpretation of VLF resistivity data is done using a one-dimensional earth model, which yields useful results as long as the electrical properties of the earth do not change laterally within a distance of about one skin depth. It is probable that within the near future inexpensive 3D computer modeling programs will become available.

In summary, VLF instruments are relatively inexpensive, one-man portable devices, which are useful for mapping linear near-surface structures such as conductive fractures and shear zones, or for mapping geology in those instances where it exhibits a simple layered-earth geometry.

HORIZONTAL-LOOP EM/GROUND CONDUCTIVITY METERS

The horizontal-loop EM technique (also known as the HLEM or Slingram method) has been used for many years for locating conductive orebodies (Grant and West 1965). To perform a survey, one man carries a small, usually multifrequency, vertical dipole transmitter coil, and a receiver operator, located

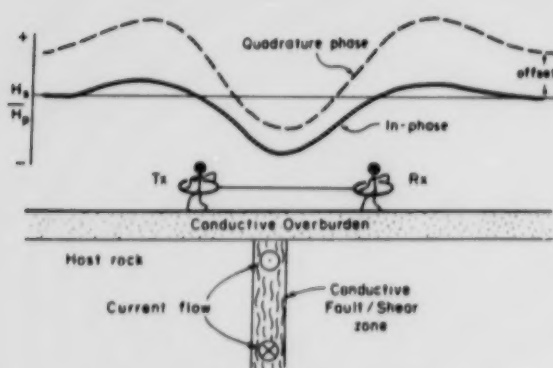


Figure 54.4. HLEM response over conductive dike. Quadrature phase response predominates over poorly conductive dikes and this component also has offset due to finite host rock and overburden conductivity.

some distance away, measures the in-phase and quadrature phase components of the vertical magnetic field at several frequencies. Typical response over a conductive vertical fault or shear zone is shown schematically in Figure 54.4. We note that as the array passes beyond the target, the in-phase component of the signal usually falls to a low value but the quadrature phase component remains offset by an amount which is, in general, a rather complicated function of the conductivity and thickness of the overburden and conductivity of the host rock. Depth of exploration is usually claimed to be about one-half the intercoil spacing, which is varied from a few tens to hundreds of metres. Free-space modeling curves are often useful with HLEM and good interpretation data is available (Ketola and Puranen 1967).

As we shall see, these systems have recently been effectively employed to map conductive faults and shear zones for groundwater exploration. In principle, the devices can also be used to map the geoelectric section in a horizontally layered earth, for which application interpretation material is readily available. This measurement requires, however, that the instrument zero-level, usually adjusted over "neutral" earth, be precisely known at each frequency, and this setting is often difficult to determine to the required accuracy. Another disadvantage of these systems is that, since the in-phase component is measured, the intercoil spacing must be closely controlled, which is difficult to do on uneven terrain. These disadvantages notwithstanding the convenient, lightweight conventional HLEM technique will undoubtedly see increasing use in groundwater exploration.

The patented electromagnetic ground conductivity meters (Figure 54.5) are a two-man portable EM device which directly measures terrain conductivity.

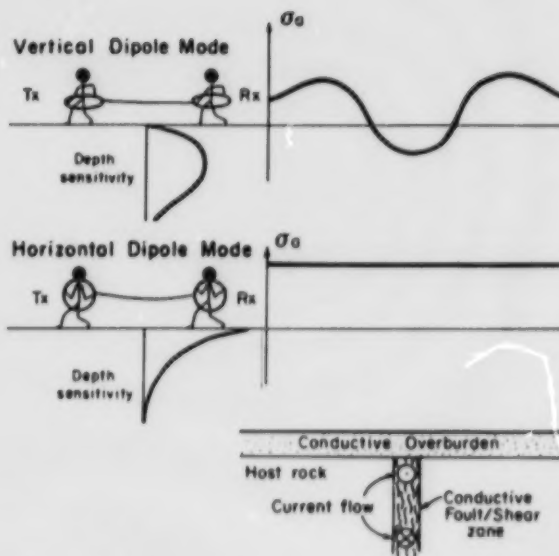


Figure 54.5. Ground conductivity meter response over conductive dike. Depth sensitivity varies with coil orientation as shown. Vertical dipole mode maximizes response to conductive dikes.

They are essentially an HLEM system with three significant differences.

1. The operating frequency is low enough at each of the intercoil spacings so that the electrical skin depth in the ground is always significantly greater than the intercoil spacing. Under this condition (technically known as operation at low induction number), virtually all response from the ground is in the quadrature phase component which, furthermore, is linearly proportional to ground conductivity so the instruments read conductivity directly (McNeill 1980). The low induction number condition also implies that the measured signals are of extremely low amplitude, and ground conductivity meters are an order of magnitude more sensitive than conventional HLEM systems.
2. The zero level of ground conductivity meters is accurately set at the factory and instruments designed so that this level stays constant with time, temperature, etc. to within about ± 1 mS/m.
3. Operation at low induction numbers means that changing the frequency proportionately changes the quadrature phase response, so that to determine variation of conductivity with depth, it is intercoil spacing rather than frequency which is varied. Ground conductivity meters are operated in both horizontal and vertical dipole modes, each of which gives a significantly different response with depth as shown in Figure 54.5; effective exploration depths for the two modes in a layered earth geometry are approximately 0.75 and 1.5 times the intercoil spacing, respectively. Since maximum intercoil spacing is

40 m, these devices have shallower exploration depth than conventional HLEM, nevertheless, they are becoming widely used for all aspects of groundwater exploration and groundwater contamination mapping. Of particular interest is the fact that when used in the vertical dipole mode, these devices are sensitive to the presence of vertical conductors such as water soaked fracture zones, whereas in the horizontal dipole mode they are quite insensitive to this type of structure and can give accurate measurement of ground conductivity in close proximity to them.

In many cases, ground conductivity meters are used in conjunction with vertical electric soundings (VES) carried out with conventional resistivity equipment. This is a natural combination since the chief advantage of ground conductivity meters is that large areas can be surveyed rapidly and inexpensively, whereas their major disadvantage is that they give limited information about variation of conductivity with depth. Conventional resistivity, on the other hand, gives good information about resistivity with depth but is expensive and time consuming to use in the profiling mode.

A recent development in groundwater geophysics is the inductive electromagnetic borehole logger (Figure 54.6) similar to those used by the oil industry for many years. These devices, which operate on the same principles as ground conductivity meters, permit measurement of the electrical conductivity of the ground outside of a plastic-cased borehole or monitoring well, while at the same time they are insensitive to the presence of the usually much more conductive borehole fluid within the casing (McNeill 1986a). An intercoil spacing of 50 cm gives reasonable vertical resolution for layered earth measurement while maintaining an adequate radial range of investigation.

TIME DOMAIN (TRANSIENT) ELECTROMAGNETIC SYSTEMS (TDEM)

The electromagnetic systems discussed above are simple, at most two-man portable devices, with maximum exploration depth of less than 200 m. The TDEM systems that are starting to be used for groundwater exploration and contamination mapping are large, complex, expensive systems requiring a crew of three or four people, with however, exploration depth from hundreds to thousands of metres. In the technique most commonly used (Keller and Kaufman 1983), a square transmitter loop, of side length of the order of the desired depth of exploration, is laid out on the ground and energized with the alternating current waveform of Figure 54.7a. This current waveform induces horizontal eddy current loops in the ground (Figure 54.7b) which expand in radius and diffuse to greater depths with passage of time. By measuring the decaying magnetic field from these eddy currents (or more accurately

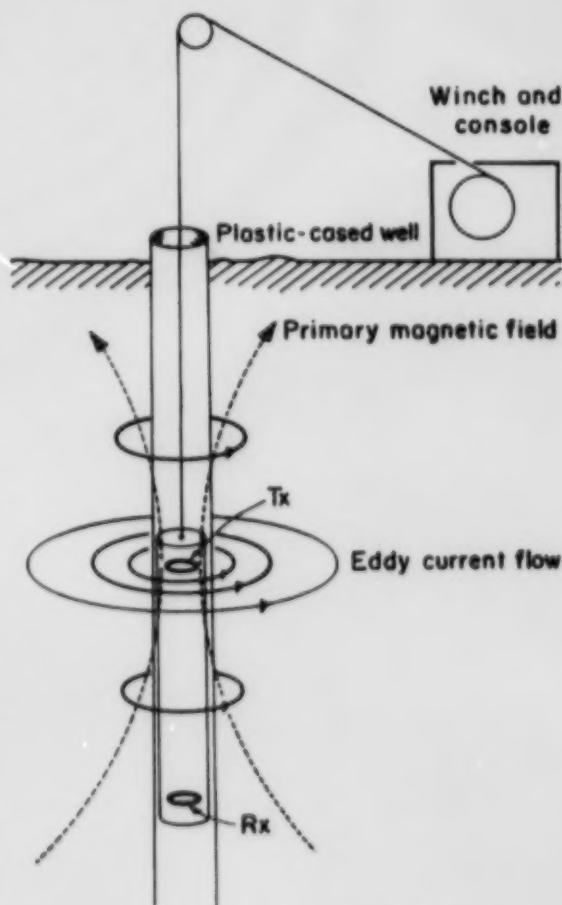


Figure 54.6. Electromagnetic borehole induction logger.

the time derivative of the decaying magnetic field, dB/dt) as a function of time, information is derived from successively greater depths. The values of dB/dt are converted to an apparent resistivity as a function of time, from which a layered earth interpretation can be made using techniques analogous to those for conventional resistivity soundings.

Such systems, which compete with large spread conventional DC resistivity systems, have several advantages and some disadvantages. A principal advantage is the high degree of lateral resolution, together with relatively good rejection of localized resistivity inhomogeneities. Since a single transmitter loop (or at most, two loops; one large, one small) is used for each sounding, the soundings are faster to carry out than conventional resistivity. Resolution of certain electrical equivalencies is also better, although the technique prefers conductive layers and is poor at resolving resistive layers. Indeed, the TDEM technique is often complementary to conventional resistivity measurements and in critical situations both techniques are used, with joint inversion

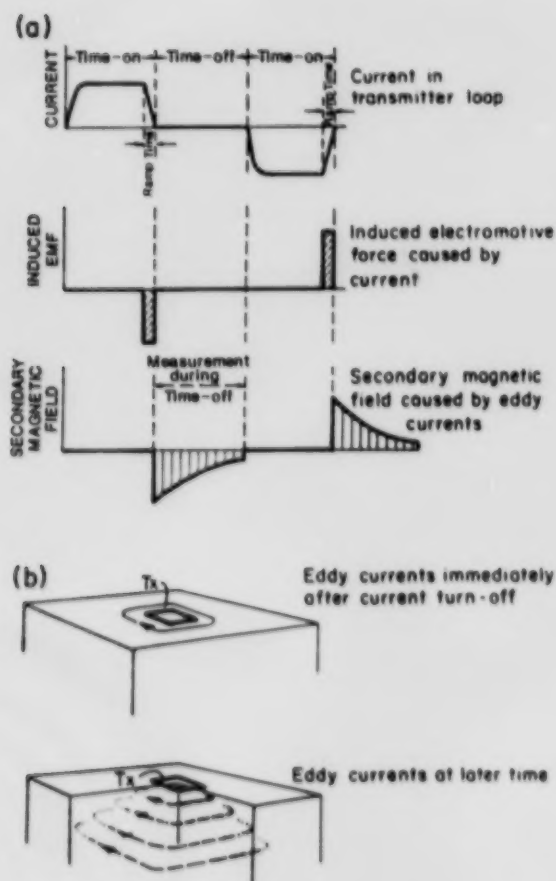


Figure 54.7. Time domain EM waveforms (a) and homogeneous halfspace eddy current flow (b).

of the data set to improve survey interpretation, particularly with respect to equivalence. The most serious disadvantage of the technique has been the high cost of the rather complex equipment. Recently, however, a shallower (150 m) less expensive TDEM sounding system has been introduced to the market.

GROUNDWATER EXPLORATION

In this section, a number of case histories illustrating use of electromagnetic techniques for groundwater exploration in various environments will be reviewed.

LOCATING FRACTURE ZONES BENEATH A CONDUCTIVE SAPROLITE IN THE BASEMENT COMPLEX IN BURKINA FASO USING HLEM, VLF, AND RESISTIVITY

Examination of the literature shows, as might be expected, that greatest emphasis is on groundwater prospecting to shallow depths of the order of 20 m,



Figure 54.8. Distribution of crystalline Basement Complex and major rift features (solid lines) in Africa (after Jones 1985).

generally in Africa. A large portion of this continent is underlain by the crystalline Basement Complex, over which lies a thick cover (which we will denote as the saprolite) of *in situ* chemically weathered overburden. Fortunately, in many regions a useable aquifer exists at the base of the saprolite, particularly where the bedrock is locally fractured. The climatic and geomorphological factors which produced the saprolite and potential aquifer are discussed in an excellent paper by Jones (1985). Figure 54.8 shows regional distribution of the Basement Complex and Figure 54.9 the lithological and hydrological characteristics of the saprolite. Note the relatively granular material produced by selective mineral decomposition and drainage at the base of the profile. Depth below ground surface to this zone of maximum intergranular porosity and permeability lies between 15 and 60 m (with most probable depth of about 20 m) and zone thickness averages 5 to 10 m. Average yields are 4 to 5 m³/hour, decreasing significantly when saprolite thickness exceeds 50 m.

Jones states that the processes controlling *in situ* weathering and landscape development are such that these saprolite aquifers are uniform over wide areas and have predictable occurrence. Since they are produced by chemical weathering, both mean an-

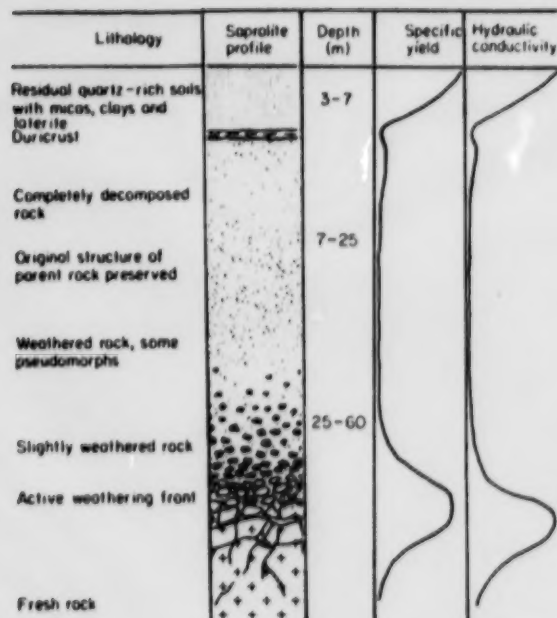


Figure 54.9. Typical saprolite profile over crystalline Basement Complex. Specific yield ranges from 10^{-1} to 10^{-5} , while hydraulic conductivities range from 10^{-2} to 10 m/day (after Jones 1985).

nual rainfall surplus and good drainage (to remove silica, the important weathering by-product) are required for their formation. Based on lithological and climatic considerations, he derived the map of Figure 54.10 showing areas with good potential for saprolite aquifer development. Over one-half the Basement Complex is included.

Palacky *et al.* (1981) used various electromagnetic and electrical techniques to locate fracture zones beneath the saprolite. They show geological sections (Figure 54.11) which are similar to those of Jones. These authors surveyed regions which were underlain by either (a) Precambrian volcano-sedimentary sequences, where depth to unweathered bedrock varied from 15 to 40 m depending on bedrock lithology (quartzite or schist) or (b) Precambrian post-Eburnian granitic intrusions, where the saprolite was less developed with shallower depth to bedrock. A resistivity sounding over the lithology (basement schist) shown in Figure 54.11a gave a thin resistive layer (2 m, 250 Ω m) overlying a thick conductive weathered zone (23 m, 18 Ω m) overlying resistive (7500 Ω m) unweathered bedrock. A sounding over terrain similar to Figure 54.11b indicated a very thin resistive layer (0.6 m, 450 Ω m), overlying a poorly developed conductive layer (8 m, 38 Ω m), overlying resistive (>500 Ω m) unweathered bedrock. We note the prevalence of the resistive surface layer.



Figure 54.10. Potential saprolite aquifer terrains in Africa (after Jones 1985).

Palacky *et al.* (1981) presented the hydrogeological section schematized in Figure 54.12 as typical of Burkina Faso. They described three types of aquifers: 1) perched alluvial aquifers in river valleys where the water table often drops seriously during dry season, and which are furthermore often contaminated; 2) aquifers in the transition zone as described by Jones, which however, in Burkina Faso are often too thin to be useful; and 3) aquifers in the fractured zones, which with sufficient fracturing can have adequate yields for rural water supplies. Furthermore, in this last case, the deep water table minimizes risk of contamination.

Such fractures can be quite invisible from the surface or air, but may be detected using geophysical techniques. Several target areas were surveyed with a multi-frequency HLEM system using experimentally optimized intercoil spacing of 50 m (25 m often failed to detect target conductors, 100 m resulted in poor spatial resolution) and measurement interval of 10 m. Best results were obtained at frequencies of 1777 and 3555 Hz. VLF surveys of tilt angle and ellipticity of the polarization ellipse were also made. Poor coupling of conductor strike with available VLF transmitters severely restricted usefulness of the VLF method in volcano-sedimentary areas, nevertheless it was used everywhere because of

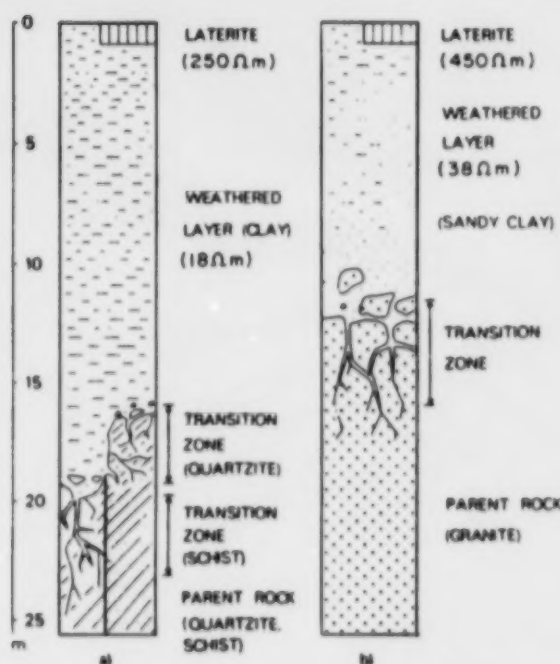


Figure 54.11. Hydrogeologic and geoelectric sections over Precambrian volcanosedimentary sequence (a) and Precambrian granite (b) in Burkina Faso. Composition, thickness, and resistivity depend on underlying lithology as well as other factors (after Palacky et al. 1981).

the speed of measurement and was particularly successful in granitic regions with reduced thickness of the weathered zone.

Figure 54.13 shows survey profiles carried out over granite with HLEM, VLF, and conventional resistivity; two anomalies show up well with all three techniques. Drilling of target B to 30 m depth produced a productive well with yield 1 m³/h. Static level was at 10 m and bedrock at 12 m.

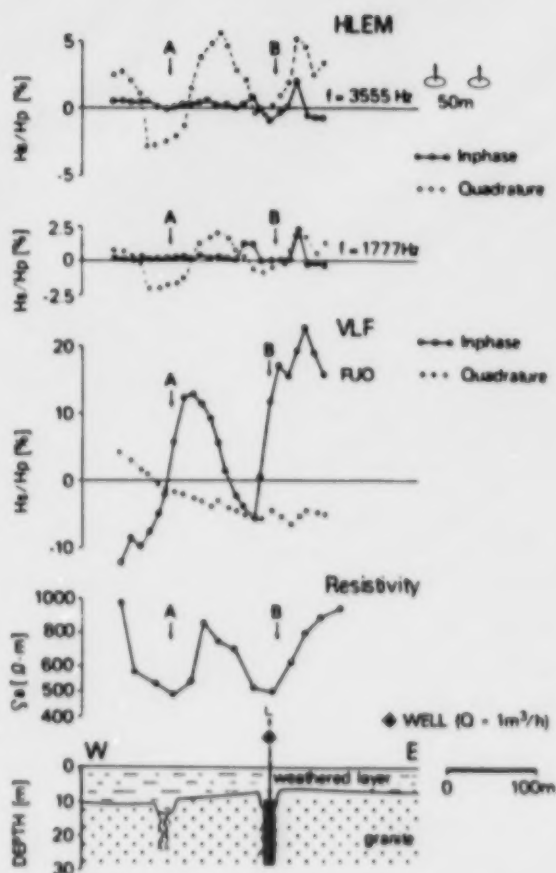


Figure 54.13. Results of three geophysical measurements obtained in granite near Rapadama. Drilling of conductor B revealed a productive aquifer (after Palacky et al. 1981).

Figure 54.14 shows similar survey profiles carried out over a volcano-sedimentary area. The thicker conductive saprolite over this lithology gen-



Figure 54.12. Schematic profile of Precambrian geology and hydrogeology in Burkina Faso. Wells can be dug (W) in soft materials but must be drilled (D) in hard rock. Note dependence of profile morphology on bedrock lithology (after Palacky et al. 1981).

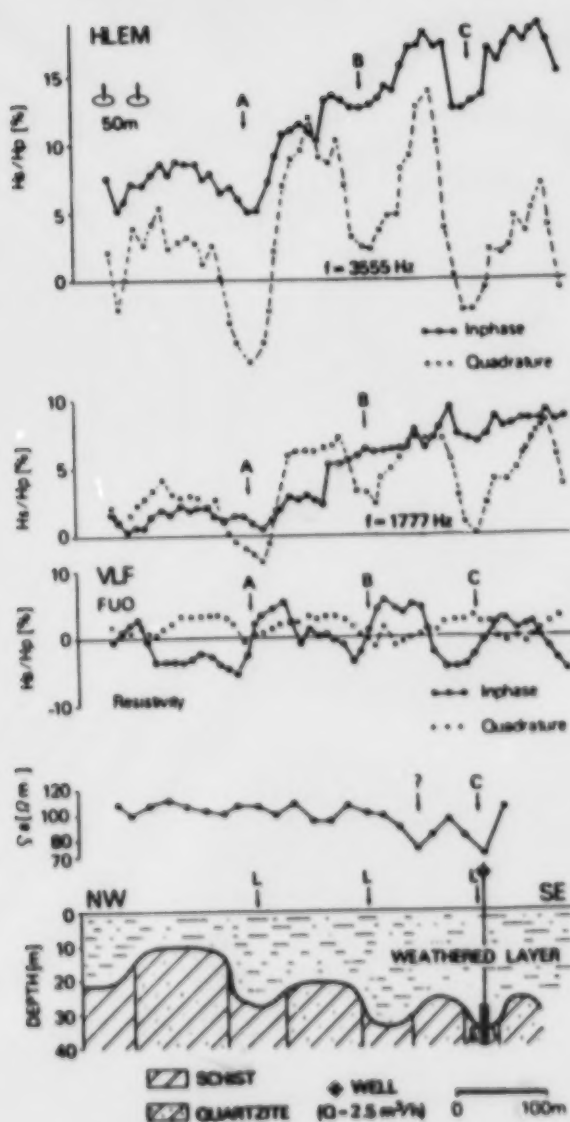


Figure 54.14. Results of three geophysical measurements obtained in volcano-sedimentary area near Mankarga. Drilling of conductor C revealed a high yield aquifer (after Palacky *et al.* 1981).

erates more active HLEM response. Despite this, three anomalies are visible on the HLEM and VLF profiles, with only one visible in the resistivity data. Drilling of anomaly C produced 2.5 m³/h from an aquifer at 29 m.

Palacky *et al.* (1981) described another area where a hole drilled on the basis of resistivity yielded 0.7 m³/h. A second well drilled 5 m southwest proved dry. A third well drilled on an HLEM/VLF anomaly 5 m northeast of the first hole gave 1 m³/h,

convincing evidence of the requirement for exact location of the anomaly for subsequent drilling.

Attempts by Palacky *et al.* (1981) to employ techniques similar to those of Koefoed and Biewinga (1976) to interpret the layered-earth geometry in the vicinity of targets (and thus, indirectly, the depth to target) were unsuccessful, probably partly due to zero-level error of the type referred to earlier and certainly due also to the many anomalies, which made the anomaly-free background zero level difficult to ascertain. Unfortunately, the frequencies, spacing, and sensitivity of conventional mineral exploration slingram systems do not yield a response which necessarily increases with saprolite conductivity and/or thickness so that simple interpretation is not possible.

It was demonstrated that use of HLEM and VLF systems, where applicable, offered two significant advantages over conventional resistivity. The first is that both systems were well suited to finding vertical conductors at the depths required for rural groundwater supplies in less developed countries, and the second was cost; Palacky *et al.* (1981) quoted that in 1979 an average cost for resistivity surveys was US\$911 and for HLEM surveys US\$239. Whilst VLF is even faster, the problems of obtaining adequate coupling to a transmitter and the shallow exploration depth in conductive material can impose serious limitations.

LOCATING FRACTURE ZONES IN THE BASEMENT COMPLEX IN KENYA USING ELECTROMAGNETIC GROUND CONDUCTIVITY METER AND RESISTIVITY

More recently, Van Lissa *et al.* (1987) have successfully employed electromagnetic ground conductivity and conventional resistivity measurements to locate well sites in Nyanza Province, western Kenya. With a population density of 240 persons per square km and a 4 percent birthrate, pre-geophysical survey efforts to locate groundwater had been unable to keep up with increasing demand, and in 1984 only 10 percent of the rural population had access to adequate water supply. The majority of the population carried water over considerable distances from natural sources which were often polluted, insufficient, or unreliable. A joint exploration program designed to take into account local socioeconomic conditions was initiated by the Kenyan government with technical and financial assistance from the Dutch government. Objective of the program was to site 750 water points in the most needy part of the province; these 750 points would suffice for approximately 300 000 people, which is 10 percent of the population of the province, giving some indication of the severity of the water problem in many parts of Africa.

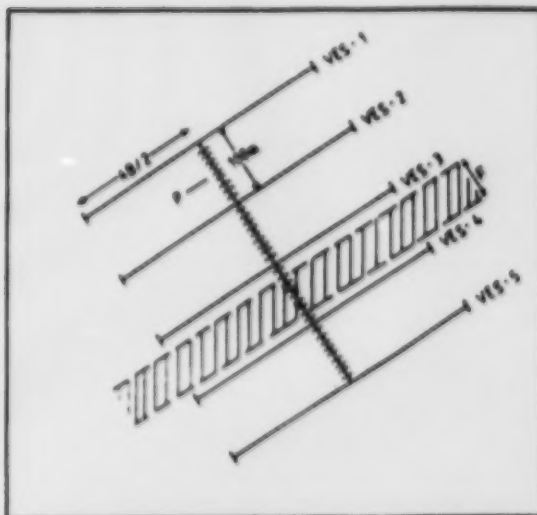
Hydrogeology of much of the area is similar to that described by Palacky *et al.* (1981) and Jones (1985), with a clay-rich saprolite overlying basic volcanic and acid intrusive Precambrian rocks or Terti-

ary basalts. Aquifers in the weathered zone generally had low yields, so efforts were again concentrated on location of faults and fracture zones overlain by a groundwater-saturated weathered zone. Initial reconnaissance using satellite imagery and air photos identified more than 3000 fault structures, with average length of 3 to 4 km over a 6000 km² area. Vertical electric resistivity sounding (VES), resistivity profiling, and electromagnetic ground conductivity meter profiling were then carried out to precisely locate the structures for accurate drilling. Figure 54.15 shows a typical survey plan. VES soundings were used first to determine weathered zone thickness and resistivity. Resistivity/conductivity profiles, using both Wenner array with "a" spacing of 10 m and an electromagnetic ground conductivity meter (vertical dipole mode) with intercoil spacing of 20 m were subsequently carried out at 10 m intervals. Typical results from such profiling, along with interpreted layered earths from soundings, are shown in Figures 54.16 and 54.17. On these profiles, the ground conductivity meter results are plotted with reversed-polarity vertical scale, that is, the conductivity increases downward so that the characteristic reduction in response due to eddy current flow in local-

ized fault structure gives upward deflection, making the structure easier to identify. The two sites of Figure 54.16a and 54.16b, located approximately 2 km apart, are on the same structure in Tertiary basalts. The ground conductivity meter data clearly indicate an anomaly at the God Bim school site. A 45 m borehole drilled exactly on the anomaly gave calculated maximum yield of 24 m³/hour. On the other hand at the Otati school site, an 85 m borehole, erroneously drilled 30 m from the indicated anomaly, proved to be dry.

Both sites of Figure 54.17 are underlain by granite. At Magina Market, the geophysical profiles (and air photos) indicate a fault contact, and a 44 m borehole gave calculated maximum yield of 7.5 m³/hour. At Angiya School, no fault structure was indicated and a 50 m borehole (drilled on other considerations) proved dry.

In areas with shallow groundwater (less than 10 m), where hand dug wells suffice, these authors found use of just air photos and field hydrogeological surveys usually gave satisfactory results. It was in areas with deeper and/or more complicated groundwater structures, that additional cost of a geophysical survey was generally justified (a 10 to 20 m hand dug well cost US\$1500 to \$2000, whereas a 50 m machine drilled well was of the order of US\$6000). Based on several years of experience, during which approximately 1000 sites were surveyed as described above, the inclusive crew costs (survey equipment, vehicle, personnel, etc.) averaged US\$47 000 per year, during which time approximately 250 sites were surveyed. This resulted in a cost of approximately US\$200 per site, or only about 3 percent of drilling costs. In many cases, results of the geophysical survey indicated that only hand dug wells were required, also yielding a substantial saving. In the case of machine drilled wells, results are summarized in Table 54.3, from which overall success rate after using geophysics went from 52 to 78 percent; average drilled depth of 65 m after geophysics was half that previously (117 m); average yield after geophysics (270 m³/day) was 2.4 times yield before geophysics (113 m³/day); finally, drilling cost per productive well fell from US\$14 000 to \$5200.



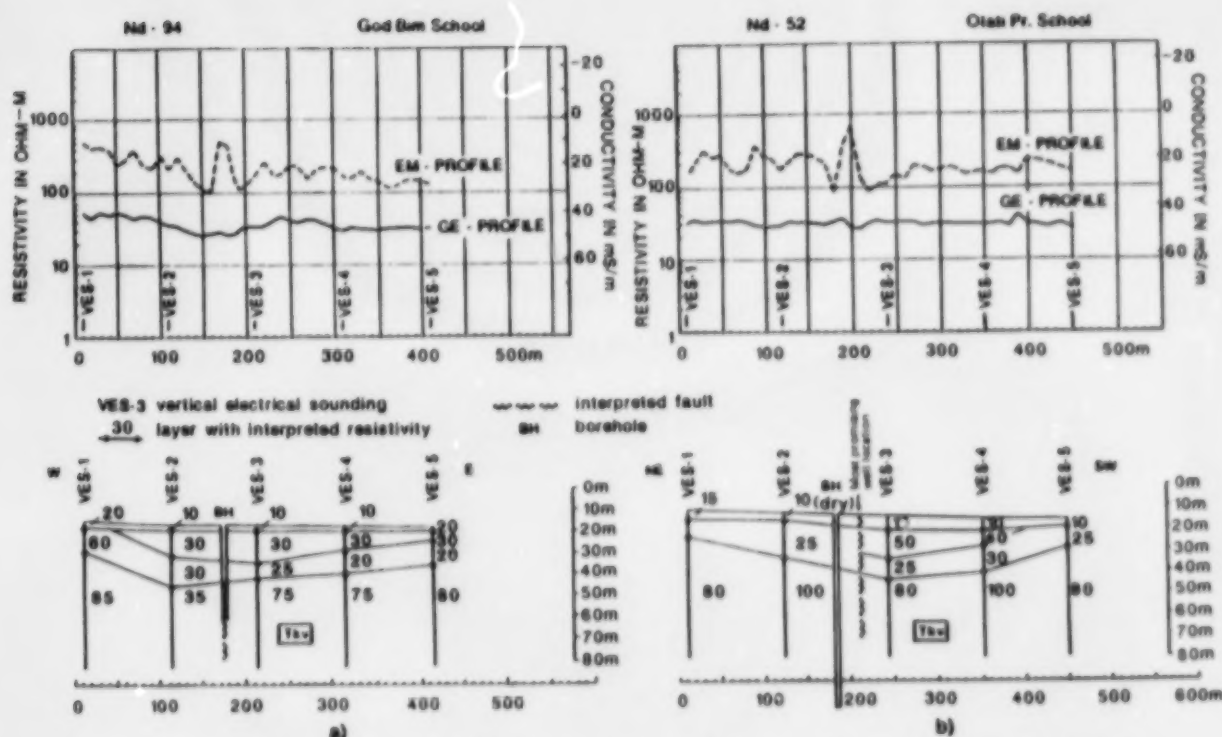
Schematic layout of geophysical survey.

- F- interpreted fracture zone from aerial photographs
- P- electromagnetic and resistivity profile direction
- VES-3- vertical electrical sounding
- AB/2- half cable length of vertical electrical sounding

Figure 54.15. Schematic layout of geophysical survey over fracture zone (after van Lissa et al. 1987).

MAPPING BEDROCK DEPRESSIONS BENEATH THE SAPROLITE IN NIGERIA, USING GROUND CONDUCTIVITY METER AND RESISTIVITY

A somewhat different approach, using resistivity and electromagnetic ground conductivity meters, has been adopted by Jones (1986) in Kano State, Nigeria, where the objective was to construct, in selected villages with a maximum population of 2000, 1000 successful boreholes fitted with hand pumps. Before using geophysics in this region, up to 40 percent of boreholes drilled into the Basement Complex had to be abandoned due to either caving or inadequate yield. Jones employed the two complementary geophysical techniques to identify those sites with suffi-



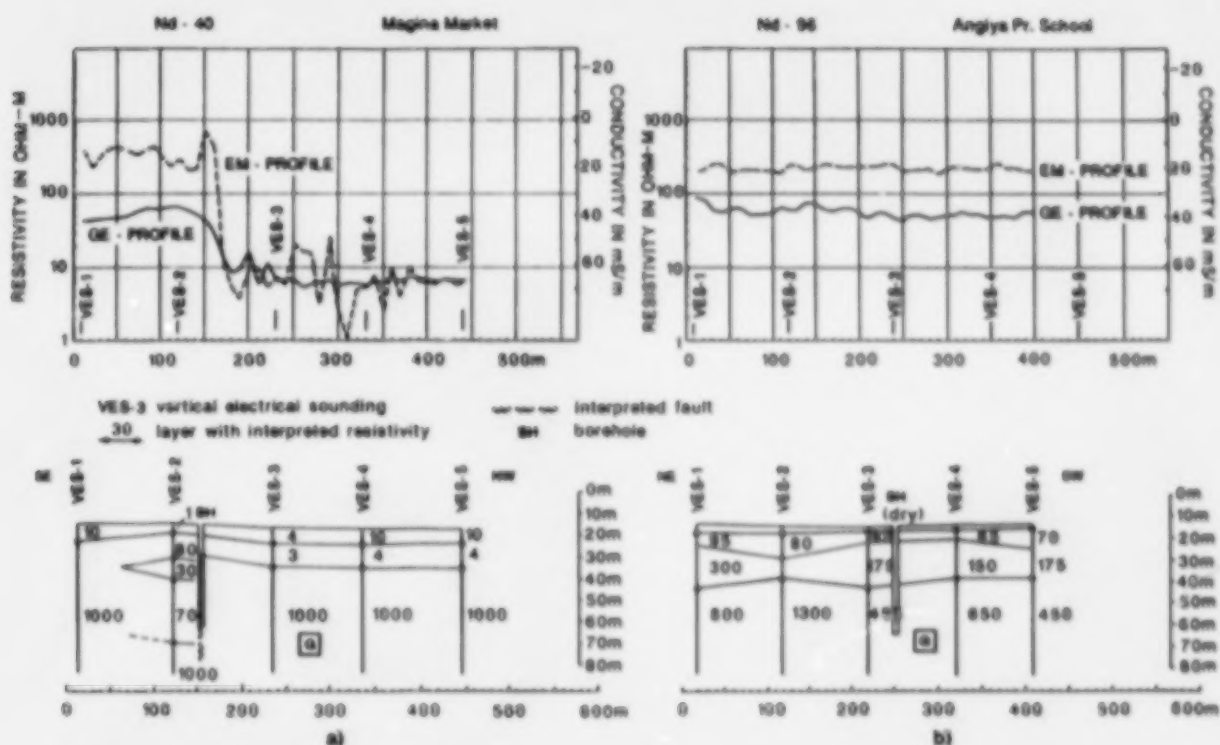


Figure 54.17. Geoelectric section interpreted from geophysical data over granites, Magina Market (a) and Angiya School (b) (after van Lissa et al. 1987).

TABLE 54.3. COMPARISON OF RESULTS AND DRILLING COSTS OF EXISTING (PREPROGRAM) AND POST-PROGRAM BOREHOLES (modified from van Lissa et al. 1987).

Rock Types	No. of Boreholes	Productive wells	Success rate (%)	Mean yield (m ³ /day)	Total length of drilling (m)	Mean depth (m)	Drilling cost per productive well U.S.\$
EXISTING BOREHOLES							
Tertiary volcanics	36	16	44	140	4536	126	24 000
Nyanzian volcanics	19	13	68	95	2204	116	10 600
Granites	7	3	43	48	490	70	10 200
Sub total	62	32	52	113	7234	117	
POST-PROGRAM BOREHOLES							
Tertiary volcanics	60	47	78	340	4080	68	5400
Nyanzian volcanics	11	10	91	94	594	54	3710
Granites	10	6	60	140	610	61	6400
Sub total	81	63	78	270	5265	65	

TABLE 54.4. GROUND CONDUCTIVITY ESTIMATES (after Jones 1986).

Estimated σ_w of groundwater	3-10	10-40	40-100 mS/m
Acceptable resistivity ρ_g	50-350	25-100	10-80 Ω -m
Acceptable apparent conductivity σ_a	>5	>12	>14 mS/m

overburden is often less conductive and VLF tilt-angle techniques can be very effective. Mullern and Eriksson (1982) have carried out many surveys in Sweden using VLF to detect faults and fracture zones in highly resistive bedrock. Such zones are important in that industrialized country both for groundwater exploration and for detecting conduits through which groundwater contamination can leak. It can be shown (Olsson 1983) that VLF response of a vertical sheet of conductance S buried in a uniform earth of resistivity ρ is controlled by the parameter $S(\rho)^{1/2}$. Thus, a structure of given S produces a much larger anomaly if located in tight 10 000 Ω m granite than 50 Ω m fractured and water-soaked lava, making conventional VLF measurements particularly appropriate to temperate climatic zones. However, it should be noted that even here the strength of the anomaly over very resistive bedrock can be significantly suppressed by a veneer of conductive clay.

A few VLF profiles from a region which exhibited many strong and weak anomalies are shown in Figure 54.18. The large anomaly on the first profile lay in a favourable position with respect to the community's existing water supply and was chosen for drilling. Borehole #1 on this anomaly yielded 4 m³/h. A second borehole, #2, was located on the second profile which was 1 km to the south of #1 in the same fracture zone; it yielded 2 m³/h. Borehole #3 on a profile midway between the others, yielded 18 m³/h. Although this data suggests correlation between yield and magnitude of the inphase VLF anomaly, other factors, even in Sweden, generally mask any relationship between these two quantities. Thus, the VLF tilt-angle anomaly locates the fracture zone but cannot be relied on to give accurate information about yield unless all other geological parameters are fixed. This fact notwithstanding, Mullern and Eriksson (1982) reported that 24 drillings made on the basis of VLF tilt-angle anomalies in various parts of Sweden resulted in average yield of 7.8 m³/h, with 80 percent of holes giving better than 1 m³/h (their criterion for a successful well). These figures are to be compared with average yields without use of VLF measurements of 0.3 m³/h in sedimentary gneiss, 0.7 m³/h in gneiss-granite, and 1.2 m³/h in Smaland granite. As a result of this success, airborne VLF surveys are now routinely flown in Sweden as part of that country's hydrogeological mapping program. It should be cautioned, however, that Sweden is anomalous in that the combination of

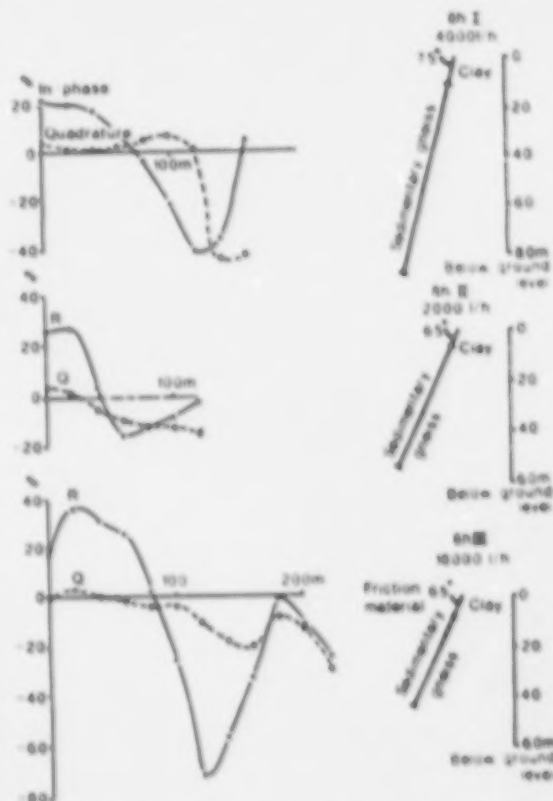


Figure 54.18. VLF anomalies and drilling results in Sweden. Note large amplitude of the anomalies (after Mullern and Eriksson 1982).

highly resistive bedrock and thin, resistive overburden make VLF a more useful tool here than in almost any other populated region in the world.

MAPPING FRACTURE ZONES IN LIMESTONE IN NEW YORK STATE USING CONVENTIONAL VLF AND GROUND CONDUCTIVITY METER

In a recent study, Yager and Kappel (1987) employed VLF tilt-angle measurements, VLF resistivity, and electromagnetic ground conductivity meters to locate bedrock fractures in limestone overlain by a thin (less than 10 m) veneer of lacustrine clay in northern New York State. Comparison of VLF tilt-angle anomalies and ground conductivity meter

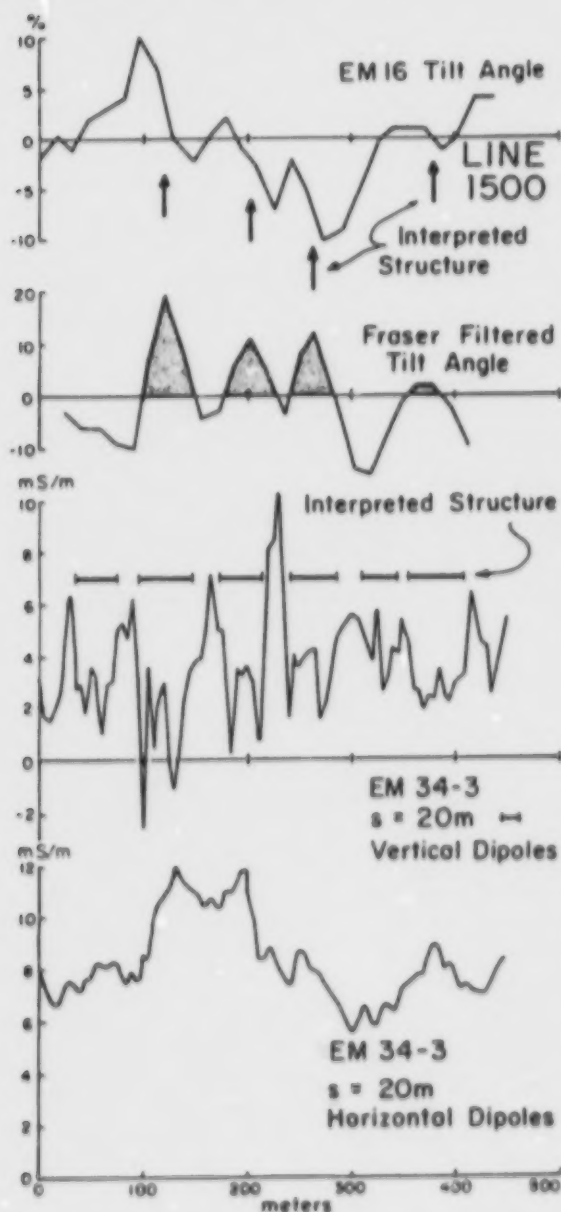


Figure 54.19. Conventional VLF tilt angle data (raw and Fraser-filtered) and ground conductivity meter data (vertical and horizontal dipole modes), Niagara, New York, (after Yager and Kappel 1987).

data is shown in Figure 54.19. Note that the vertical dipole data is plotted in the normal fashion (conductivity increasing upward), so that the characteristic anomalies from vertical sheet conductors show rapid excursions in the direction of decreasing conductivity, as shown in Figure 54.5. From Figure 54.19 it is seen that, while tilt-angle measurements correctly locate fractured zones, the ground conductivity me-

ter in the vertical dipole mode with intercoil spacing of 20 m identifies individual fractures and locates them to high accuracy. Furthermore, measurements in the horizontal dipole mode are seen from Figure 54.19 to be quite insensitive to the presence of fractures (relatively weak eddy currents being induced in them with this mode), and horizontal dipole data continues to give good indication of conductivity and thickness of the overburden. Thus, correct survey procedure for accurately locating small fractures would be to use the fast VLF technique to localize anomalous zones, and to then use the ground conductivity meter in both horizontal and vertical dipole modes, with measurement spacing of 5 m or even less, to locate individual fractures.

GROUNDWATER CONTAMINATION DETECTION AND MAPPING

The increasing concern with groundwater contamination in the United States in the past decade has seen the extensive application of electromagnetic techniques to groundwater contaminant mapping. There are now many tens of papers in the groundwater contamination literature describing different uses of ground conductivity meters for mapping this recently realized threat to near surface aquifers.

Basically, electromagnetic instruments map the existence and approximate level of contamination by mapping ground conductivity. As we have seen in the section "Factors Affecting Terrain Conductivity", addition of 25 ppm of ionic material to groundwater increases the ground conductivity by approximately 1 mS/m. The problem is to detect and map the plume in the presence of conductivity variations caused by other parameters such as changing lithology etc. Highly contaminated areas are the easiest to map since other factors will have a proportionately smaller effect. It is, in theory, also possible to map organic contaminants (insulators) by virtue of the reduction in conductivity; but, except for exceptional cases of electrically homogeneous background or very high levels of contaminant, organic materials are difficult or impossible to detect, certainly at the ppb levels which can still be a serious problem for many toxic organic substances. Fortunately, in many cases where dangerous organic substances are present, there are ionic materials as well, and the plume is mapped on the theory that the concentration of one is essentially the same as the other, a fact which may or may not be true. In any case, the size of the plume established using conductivity or resistivity measurements will almost always be smaller than the size determined by direct groundwater sampling.

Because of the problem of spurious conductivity variations caused by other geological parameters, the use of electromagnetic surveys should be confined 1) to locating initially and mapping the approximate extent of contaminated groundwater in order to more accurately study the problem using direct sampling methods, and 2) to estimating the degree of

contamination for ranking purposes. Electromagnetic techniques are also used to map lithological structures which might control contaminant movement. In the future, electromagnetic measurements will also undoubtedly be used to assist in locating new landfill sites, which should be thoroughly mapped before use so as to determine the electrical background against which subsequent changes will have to be measured.

The big advantage of electromagnetic methods for groundwater contamination is that large areas can be surveyed quickly and inexpensively, and small variations in conductivity detected. These features are important since spatial pattern recognition is a basic feature of the interpretation. For this reason, good knowledge of the local hydrogeology is also essential to a successful interpretation.

MAPPING ACID MINE DRAINAGE IN A RECLAIMED COAL MINE IN APPALACHIA USING GROUND CONDUCTIVITY METER AND RESISTIVITY

Our first case history will deal with acid mine drainage (AMD) in a rehabilitated surface coal mine in Appalachia. Ladwig (1982) described how the specific conductance of groundwater in areas of high AMD can vary from 1000 $\mu\text{S}/\text{cm}$ to as high as 10 000 $\mu\text{S}/\text{cm}$ due to oxidation of pyrite (associated with coal and coal-bearing strata) to form sulphuric acid. These values of specific conductivity correspond to σ_w from 100 to 1000 mS/m and, using the relationship discussed in the section "Factors Affecting Terrain Conductivity", result in values of σ_a varying from approximately 25 to 250 mS/m.

At regraded and reclaimed surface mines, AMD often occurs as seepage from spoil (waste) material which has been used to resurface the mine as part of the reclamation effort. In the simple case shown in Figure 54.20, the coarse spoil backfill which has been added acts as a perched aquifer overlying the relatively impermeable coal underclay on the mine floor (pavement). Discharge of AMD will take place through one or more seeps on the hydraulic downgradient side of the site if the perched groundwater contacts weathered pyrite material. Com-

monly, the seep occurs long after the site has been regraded and revegetated. To comply with U.S. federal regulations, the operator must treat the discharge or attempt at-source abatement procedures. The latter obviously requires geographic location of the source(s).

In this case history, the sources were associated with pockets of preparation plant refuse (pyritic and highly acid-producing) which had been buried in coarse sandstone backfill. The latter will have low conductivity when dry, relatively low conductivity when saturated with AMD-free water, and high conductivity in the presence of AMD. Lateral boundaries of the survey area, assumed to be of similar, undisturbed material will also exhibit relatively low conductivity if clay-free. Drainage from the site shown in Figure 54.20 is from a small stream flowing to the southwest. A perennial seep issuing from the soil near the stream discharges water which contains 5000 mg/L sulphates, 4000 mg/L acidity, 800 mg/L iron, and 275 mg/L aluminum, at the rate of 0.13 L/s.

Survey results are shown in Figure 54.21. Measurements were taken with an electromagnetic ground conductivity meter in the horizontal dipole mode at both 10 and 20 m intercoil spacings (10 m data is shown). Ten survey lines, at spacing 25 m, resulted in 200 data points for each spacing; the survey took two days to complete. Drill logs from eight existing

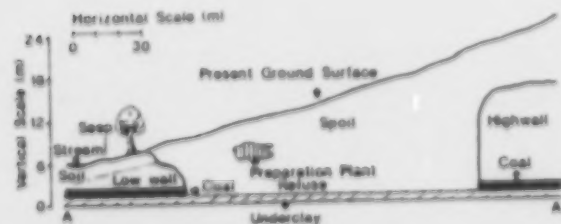


Figure 54.20. Coal mine cross-section (A-A') showing backfill (spoil) and preparation plant refuse (after Ladwig 1982).



Figure 54.21. Contours of apparent conductivity from ground conductivity meter survey. Section A-A' is indicated in Figure 54.20 (after Ladwig 1982).

observation wells (A-H) and five new wells (T, U, X-Z) were correlated with the EM survey results.

In general, conductivity values of the order of 6 to 10 mS/m are consistent with a porous granular material reasonably well drained or containing non-mineralized groundwater. Superimposed on this background are two steep peaks (one complex), where conductivities rise above 20 mS/m. Wells F, G, and X were the only wells to encounter buried refuse (well W was not drilled at the time of writing), and all three are at or near the centre of the high conductivity zones. At wells F and X, the refuse is about 3 m below surface, whereas at well G a thin layer was encountered 10 m below surface. The water table at well F is about 3 m below the surface, that at well X, 16.2 m below surface. In fact, the only region where the water table is within 10 m of the surface is at the southern end of the area; the small lobe near well D corresponds to the direction of groundwater flow to the seep (as the result of placement of a permeability barrier just to the west of the well). It is apparent, then, that in the area of wells X and W, where depth to water table is large, the shape and values of apparent conductivity show that the conductivity highs are due to vertically draining areas of acidity. Farther to the south, the conductivity high is reflecting both increased acidity and proximity of the water table.

MAPPING THE VERTICAL AND LATERAL DISTRIBUTION OF A CONTAMINANT PLUME IN NEVADA USING GROUND CONDUCTIVITY METER AND INDUCTION BOREHOLE LOGGER

This case history from McNeill *et al.* (1988) illustrated the use of an electromagnetic induction borehole logger in monitoring wells to map subsurface contamination. Pittman, Nevada, is a small community that has been industrialized for many years, a result of which is a large groundwater contamination plume leading northward to the Las Vegas Wash, which drains into Lake Mead, the water supply for Las Vegas. The plume, as outlined by contours of total dissolved solids from groundwater sampling, is shown in Figure 54.22, which also indicates location of the Pittman transect, along which are spaced a series of 10 cm diameter plastic-cased monitoring wells on 70 m centres. Location and depth of the wells is shown in section in Figure 54.23, which also shows the hydrogeologic section of alluvial sand and gravel overlying a clay aquitard. Profiles over the transect using ground conductivity meters with intercoil spacings of 3.67, 10, 20, and 40 m, shown in Figure 54.24, indicate a major plume between wells 635 and 651, with a smaller, subsidiary plume in the vicinity of well 627. Relative size of the two anomalies at different intercoil spacings suggests that the first plume extends from very near surface to deeper than 10 m, whereas the second plume exists primarily at depths in excess of a few metres.

Sixteen of the monitoring wells were mapped with an induction logger (intercoil spacing 50 cm) in two days. The actual time to log a well was a few minutes. Most of the time at each site was spent performing necessary cleansing operations to prevent cross-contamination of the wells. Contours of apparent conductivity in Figure 54.25 confirm more or less continuous contamination with depth near wells 637 to 639 and increasing contamination with depth near wells 625 to 627. Of interest is the lateral and vertical complexity of the plume (more evident in the individual logs) even in this relatively simple hydrogeological environment, sufficiently complex that inferences of the vertical plume distribution from conventional DC soundings would be largely in error. Also of interest is the fact that, even in a sandy environment where the capillary fringe is probably of relatively small extent, location of the water table is poorly defined electrically and would not be detectable from surface electrical measurements. Significant contamination exists in the vadose zone but the most severely contaminated area lies at the base of the aquifer and probably also within the clay aquitard itself.

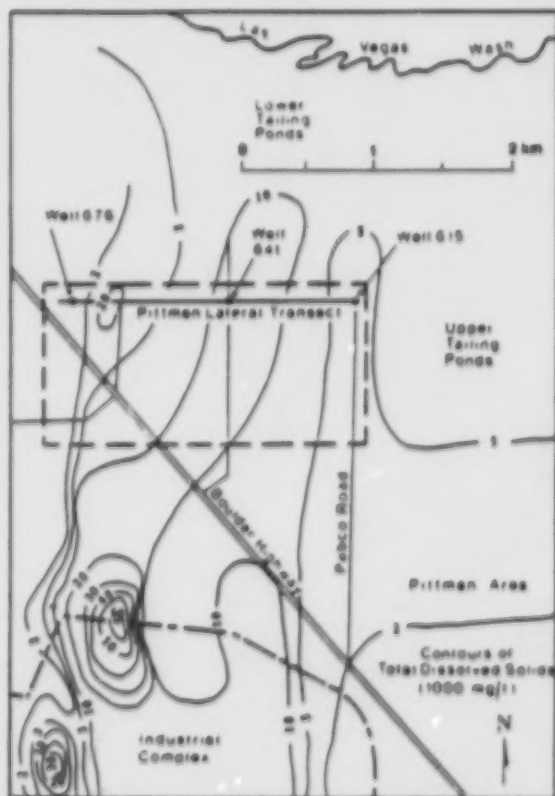


Figure 54.22. Groundwater contaminant plume, Pittman, Nevada, as outlined by contours of TDS (after McNeill *et al.* 1988).

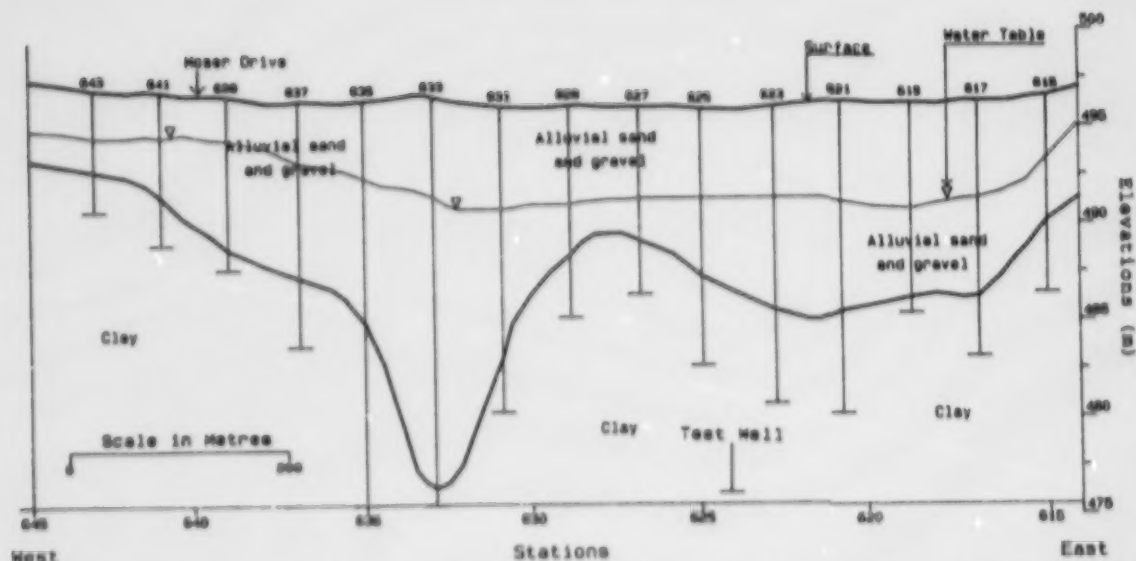


Figure 54.23. Hydrogeological cross-section, Pittman transect showing location of monitoring wells (after McNeill *et al.* 1988).

SALINE INTRUSION MAPPING

From the material presented thus far, it will be evident that electromagnetic methods, with their sensitivity to subsurface conductors, are well suited to mapping the extent of saline intrusion into coastal aquifers, as confirmed by a number of studies. Once again, the objective of these surveys is to provide guidance to the hydrologist for siting monitoring wells.

MAPPING COASTAL SALINE INTRUSION IN STACKED AQUIFERS IN CALIFORNIA USING TDEM

Mills *et al.* (1987) used TDEM resistivity sounding techniques to map the inland extent of encroaching saline intrusion in fresh water aquifers in the Salinas Valley at Monterey, California. A hydrogeological section is shown in Figure 54.26. The 50 m aquifer, the most heavily utilized source of groundwater in the area, has salt water intrusion inland to a distance of 8 km. As this aquifer becomes more contaminated, wells are abandoned and search for fresh water begins in the 120 m aquifer, currently less mineralized.

Figure 54.27 shows location of the site, the 100 soundings, and also profiles A-A' and B-B', along which geoelectric sections were interpreted. Survey objective was to map the inland position of the 500 mg/L isochlor in the two aquifers. Survey data was calibrated by taking soundings in the vicinity of test wells, which resulted in a value of 8 Ω m being adopted as indicating the 500 mg/L level of chloride

ion. Interpreted geoelectric sections along A-A' and B-B' are shown in Figure 54.28 and inferred location of the 500 mg/L isochlor for the two aquifers is shown in Figure 54.29 together with the position as determined directly from test well data. Agreement is quite reasonable.

SOIL SALINITY MAPPING

For the reasons described earlier, electromagnetic techniques are also well suited for mapping soil salinity to depths useful for the agriculturalist (the root zone, approximately 1 m) and many salinity surveys have been carried out with electromagnetic ground conductivity meters. By far the most serious problem, in terms of area affected, is that of salinity in irrigated farmland where, as a result of poor drainage design, the water table in recently irrigated areas (post World War II) has risen to within a metre or so of the surface. At this level, in arid climates, rapid transport of water to the surface as a result of capillary action and evaporation takes place, with the unfortunate consequence that previously dissolved salts are left behind to hinder plant growth (McNeill 1986b). Similar effects also take place under dryland conditions when the water table approaches the surface. In either case, the result can be highly variable soil salinization (as illustrated in Figure 54.30), which is difficult to map accurately over large areas.

To measure shallow salinity, an electromagnetic ground conductivity meter with short intercoil spacing (a few metres or less) is necessary. Fortunately, the values of conductivity which result from agriculturally damaging salinity levels are relatively high

Measurement interval EM31 - 5 m, EM34-3 - 10 m

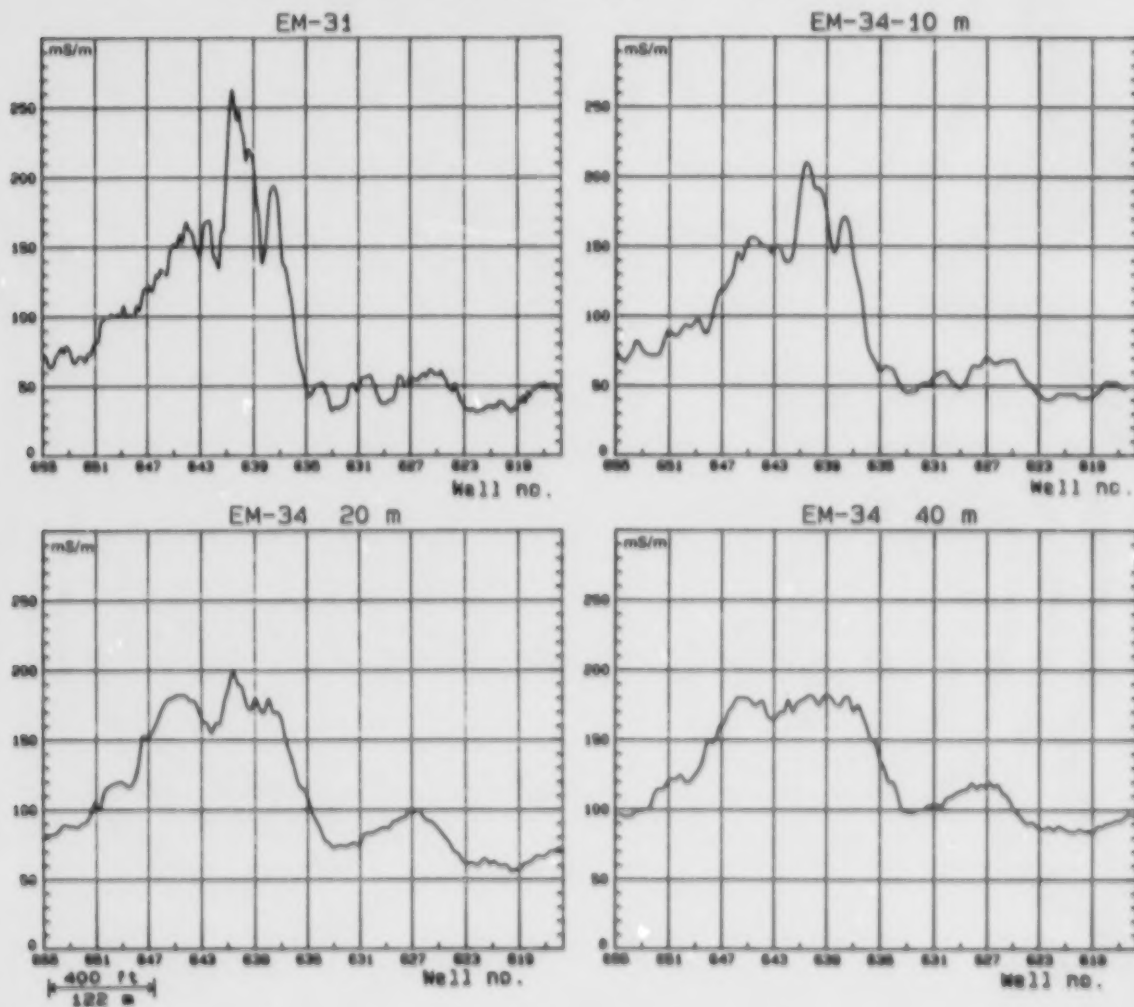


Figure 54.24. Ground conductivity meter profiles along Pittman transect (after McNeill et al. 1988).

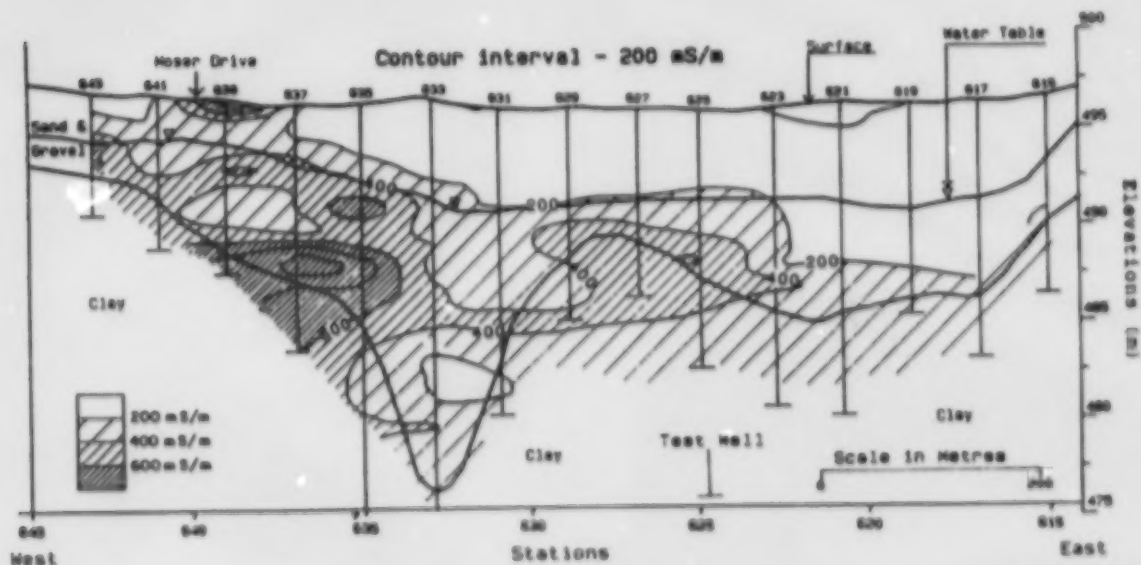


Figure 54.25. Contours of apparent conductivity measured with induction borehole logger at Pittman transect (after McNeill et al. 1988).

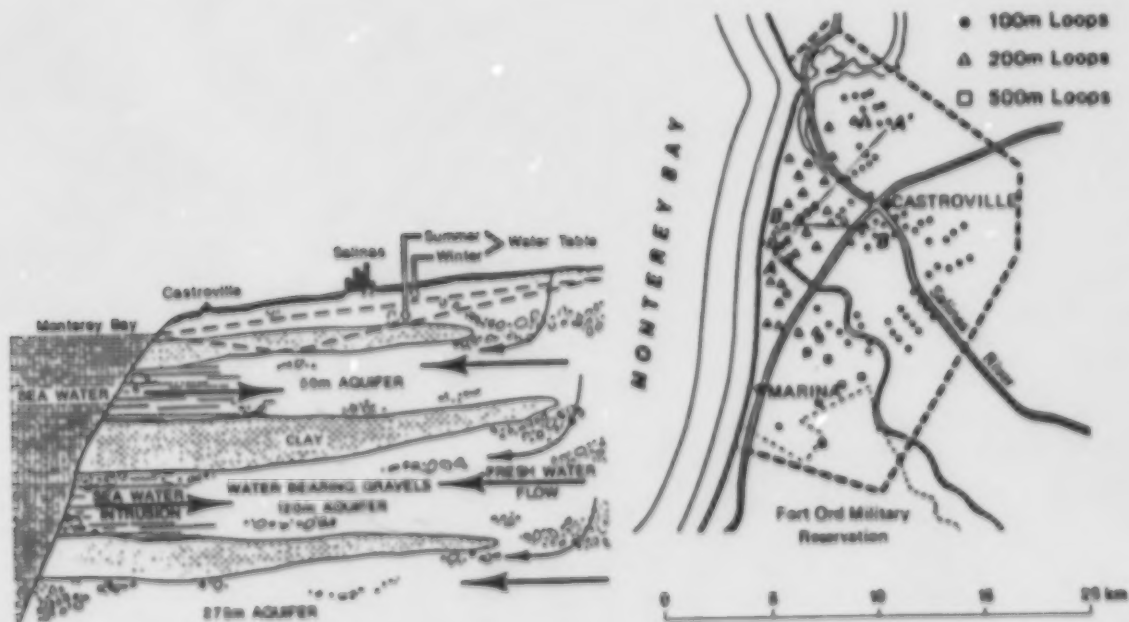


Figure 54.26. Hydrogeological cross-section, northern Salinas Valley (after Mills et al. 1987).



Figure 54.27. TDEM transmitter loop (sounding) location map. Note profiles A-A' and B-B' with reference to Figures 54.28 and 54.29 (after Mills et al. 1987).

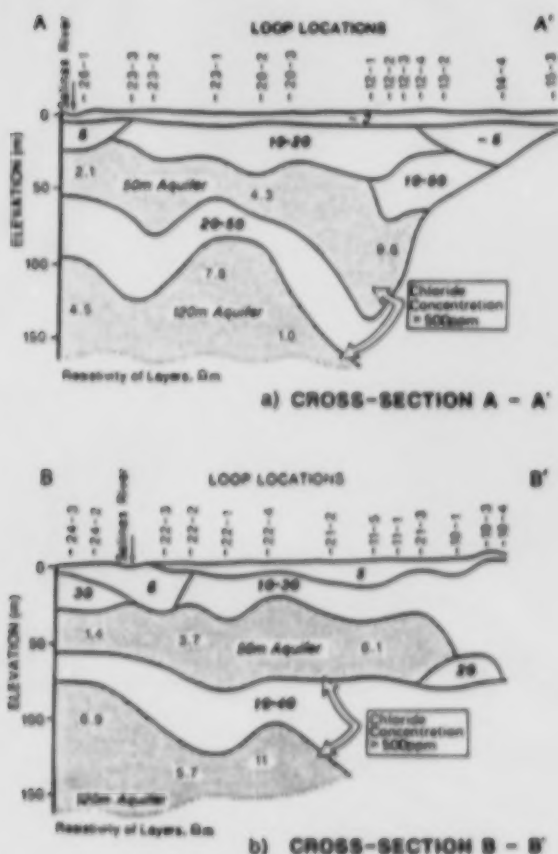


Figure 54.28. Interpreted geoelectric section from TDEM data and well data along profile A-A' (a) and profile B-B' (b) (after Mills et al. 1987).

and interfering effects from varying soil structure, clay content, etc. can usually be ignored. Equally importantly, since salt is hygroscopic, those areas which are highly salinized seem to retain enough soil moisture to keep the conductivity at measurable levels even when the soil itself is relatively dry.

MAPPING DRYLAND SALINITY IN WESTERN CANADA USING A GROUND CONDUCTIVITY METER

The results of a high spatial resolution survey of soil salinity (Wood 1987) carried out over dry farmland in Alberta are shown in Figure 54.31. For this survey, an electromagnetic ground conductivity meter of intercoil spacing 3.7 m was mounted, in the vertical dipole mode, on a trailer which was in turn towed behind a small four-wheeled all-terrain vehicle. The surveyed area was 1600 m long by 750 m wide; the 16 survey lines were spaced 50 m apart resulting in a total survey of 25 line km, which was surveyed in about 7 hours. Data was collected automatically every 5.5 m by triggering a digital data log-

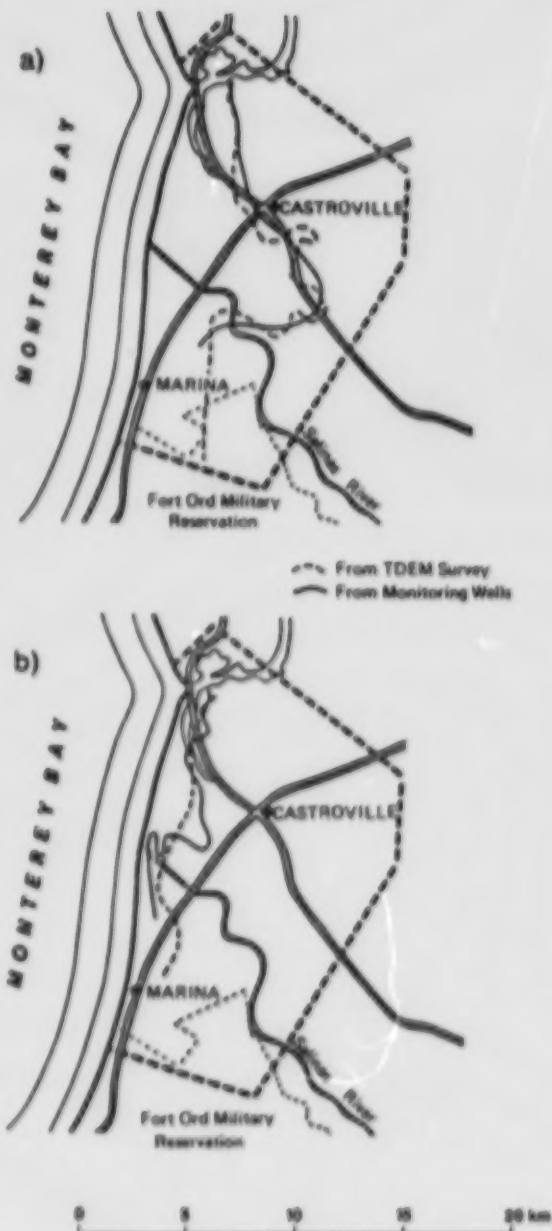


Figure 54.29. Location of 500 ppm isochlors in the "50 m" (a) and "120 m" (b) aquifers from TDEM data (after Mills et al. 1987).

ger from a magnet mounted on one of the trailer wheels. The tractor was kept on survey line by personnel stationed at each end of the line (and also at intermediate points where necessary), who were equipped with VHF radios to communicate with the driver and each other.

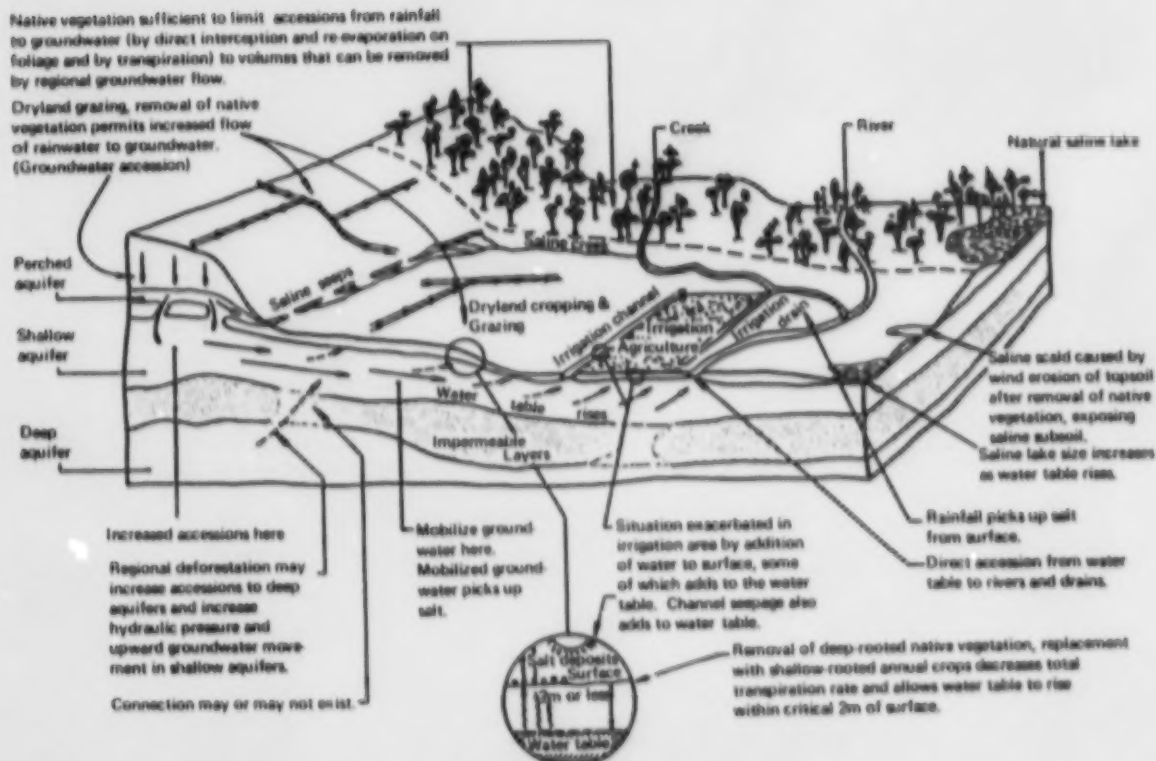


Figure 54.30. Factors controlling salinity (after Gutteridge et al. 1983).

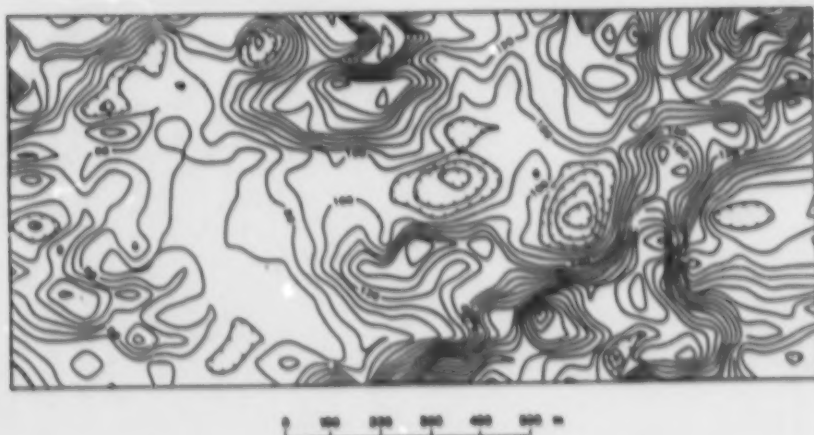


Figure 54.31. Contours of apparent conductivity (mS/m) measured with ground conductivity meter over dry farm land, Alberta, Canada (after Wood 1987).

The survey area had been leased from the owner by the Canadian Government with the intention of attempting to reclaim the land. Thus, there were two purposes behind the survey; the first was as a diagnostic tool with which to determine factors controlling soil salinity under the various conditions of topography, soil structure, moisture content, etc. that existed over the site, the results of which would be used to provide guidance in locating test holes and observation wells. The second purpose was to define, as completely as possible, the initial spatial extent of the salinity for comparison after reclamation efforts.

Survey results are shown in Figure 54.31 where the data has been contoured directly in σ_a (mS/m). The complexity and serious extent of the salinity are immediately obvious. Conductivity ranges from a low of 58 mS/m, typical of unsalinized Prairie soils, up to 300 mS/m, a value indicating extreme salinity. Approximately 25 percent of the total area is over 160 mS/m, a value indicating high salinity.

The survey revealed and mapped extensive subsurface salinity, not apparent by surficial expression, and identified these areas most immediately threatened. Such surveys, using ground conductivity meters (but not usually at such high spatial resolution) are routinely carried out throughout western Canada to assess the severity and extent of soil salinity on a farm by farm basis.

FURTHER EXAMPLES

In addition to the case histories given above, there are now many other published examples illustrating the application of electromagnetic techniques to groundwater studies. Lindqvist (1987) reported that use of HLEM for groundwater exploration increased the success rate in difficult areas from 55 to 80 percent and that the Swedish Geological Company (SGAB) had effectively used the technique in Cameroon, Kenya, Nigeria, and Zimbabwe. Cratchley, Hazell and Dickenson (1987) used resistivity VES and electromagnetic ground conductivity meters to locate and quantify concealed sand aquifers beneath alluvial plains in northeast Nigeria in the Chad Basin. Poddar and Rathor (1983) used the VLF resistivity technique to measure resistivity and thickness of the saprolite in southern India. Van Kuijk, Haak, and Ritsema (1985) employed joint inversion of VES and ground conductivity meter soundings performed in west Sudan to reduce the equivalence associated with other technique used alone.

In a tutorial paper, Fitterman and Stewart (1986) calculated the transient electromagnetic response for a variety of geoelectrical targets at depths of hundreds of metres to determine the conditions under which the TDEM technique would be effective for groundwater exploration. Fitterman (1986) used TDEM techniques to determine quality of

groundwater within the Michigan basin by mapping the location and depth of highly mineralized and therefore conductive zones. Stewart (1982) used an electromagnetic ground conductivity meter to map coastal saline intrusion in Florida. And, finally, there are many tens of papers in the groundwater contamination literature describing different applications of ground conductivity meters to mapping this recently realized threat to near surface aquifers.

SUMMARY

In this paper we have illustrated, using selected case histories, or referred to (in the section "Further Examples") various groundwater problems solved by using electromagnetic methods, often in conjunction with conventional DC measurements, sometimes alone. These have included:

1. mapping fracture zones beneath an electrically conductive saprolite or a resistive overburden
2. locating bedrock depressions beneath the saprolite
3. locating granular aquifers in alluvial deposits
4. sounding thickness and resistivity of water-bearing strata (including joint use of electromagnetics and VES to reduce equivalence)
5. mapping groundwater contamination and highly mineralized zones in aquifers
6. mapping soil salinity

Most of the cited surveys have been carried out in the recent past, and it is apparent that electromagnetic techniques are now playing a major role in many groundwater applications. Although the various electromagnetic techniques have different advantages, the principle reasons for their increased use are:

1. speed of operation and thus low cost of surveys
 2. ability to work through resistive surficial layer
 3. ability to detect anomalies at relatively low levels of conductivity contrast
 4. improved lateral resolution compared with conventional resistivity
 5. complementary (compared with resistivity) resolution of electrical equivalence
- Relative disadvantages are:
1. high initial cost of equipment
 2. the fact that interpretive techniques are still being developed
 3. Electromagnetic techniques are usually more effective in looking for conductive rather than resistive material.

In general, the advantages outweigh the disadvantages and, particularly for reconnaissance surveys, electromagnetic techniques are proving very effective indeed.

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55. Ground Penetrating Radar for High Resolution Mapping of Soil and Rock Stratigraphy

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ABSTRACT

Ground penetrating radar is a technique which offers the capability of viewing shallow soil and rock conditions with new eyes. The requirement for a better understanding of overburden conditions for activities such as geochemical sampling, geotechnical investigations, and placer exploration, as well as the factors controlling groundwater flow has generated an increasing demand for techniques which can image the subsurface with higher resolution than heretofore possible.

The application areas for ground penetrating radar are diverse. Ground penetrating radar has been used successfully to map ice thickness on frozen rivers, water depth in fresh water lakes, bedrock depth, soil stratigraphy, and water table depth as well as to delineate rock fabric and to detect voids and karst features to name some of the more exploration and

mine development relevant applications. In this presentation, the effective application of the radar to high resolution definition of soil stratigraphy is highlighted.

The basic principles and practices involved in acquiring high quality radar data in the field are illustrated by selected case history examples. In particular, one case history shows how radar has delineated five soil horizons to a depth in excess of 20 m. In all instances, the corroboration of the radar results by borehole investigations demonstrates the power and utility of the high resolution radar method as an aid for interpolation and extrapolation of the information obtained with conventional coring programs. With the advent of new instrumentation and field procedures, the routine application of the radar method is becoming economically viable and the method will continue to see expanded use in the future.

56. Applications of a Shallow Seismic Reflection Method to Groundwater and Engineering Studies

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ABSTRACT

Over the last decade, instrumentation has been developed that allows the application of seismic reflection methods to groundwater and engineering problems. At the Geological Survey of Canada, we have been developing and testing shallow reflection techniques for mapping the bedrock topography and structure within the overburden. We have attempted to develop methods which can be implemented with a minimum investment in equipment and computing capabilities. The data are recorded on a 12-channel engineering seismograph, using a single high-frequency geophone per channel, and a hammer or in-hole shotgun ("Buffalo gun") as the seismic source. Processing and display of the data can be accomplished on an Apple II+ or IIe microcomputer and an Epson wide-track dot matrix printer.

The successful application of any shallow seismic reflection method depends on the ability of the ground to transmit high-frequency seismic energy. Optimum conditions in this regard are found at sites where the surface materials are fine grained and water saturated. In such areas, reflection data with dominant frequencies of 300 to 500 Hz have been recorded, with potential subsurface structural resolution of approximately 1 m. However, when the surface materials are coarse grained and the water table is several metres below the shot and geophones, the dominant frequencies of reflection data can be less than 100 Hz. In such areas, whether or not seismic reflection methods are viable will depend on the resolution required and the depth to the target horizon.

The "optimum offset" shallow seismic reflection method has been used to map bedrock from as shallow as 15 m below surface to as deep as 400 m below surface, and to map such features as foreset bedding, unconformities, and top of till within the overburden. Shallow reflection methods should now be considered as one of the geophysical techniques applicable to groundwater and engineering problems.

INTRODUCTION

Seismic reflection methods have been the primary geophysical tool used in oil and gas exploration for over 50 years. Because of the tremendous commercial importance of oil, much industrial research and

development has been invested in this branch of geophysics. By the 1960s, specialized field procedures, digital magnetic tape recording, and computer processing of the data had become standard in the industry. Conventional seismic reflection techniques are now well advanced in comparison to other geophysical techniques, but require considerable investment in sophisticated recording equipment and computer processing capability.

Shallow seismic reflection methods, commonly called high-resolution reflection methods, also began with oil-related prospecting. By the early 1970s there was considerable interest in examining shallow stratigraphic traps as sources of oil and gas. To examine high-frequency reflections from shallow horizons required both improved digital recording equipment and seismic detectors (geophones). Such equipment is now available, and is continually being improved. Seismic data in which reflection events have dominant frequencies above 100 Hz are generally considered to be "high-resolution" data. The depth of penetration of "high-resolution" techniques ranges from tens to hundreds of metres. In contrast, conventional reflection techniques utilize the frequency range between 10 and 90 Hz, with depths of penetration in the thousands of metres.

While seismic reflection methods have been well established in the oil industry for decades, equipment acquisition, field work, and data processing have been prohibitively expensive for engineering, groundwater, geotechnical, Quaternary mapping, or placer exploration applications. Refraction, rather than reflection, methods have been used almost exclusively in these fields when subsurface structural information was required. Refraction methods depend on the measurement of only the time of first arrival of seismic energy at a series of source-receiver separations, and so do not require digitization of the seismic wave train or computer processing of the data. Thus, refraction surveys can be carried out with relatively simple and inexpensive equipment. For over thirty years, seismic refraction methods have been used to obtain estimates of the depth to bedrock and, where possible, to determine the major lithologic boundaries within the overburden.

The limitations of refraction techniques are: a) the basic assumption that velocity increases with depth; b) the large source energies required to obtain refractions from horizons deeper than 20 or 30 m below surface; and c) the difficulty in resolving

any detailed structure on the target horizon. Reflection techniques can overcome many of these problems. Energy will be reflected back to the surface from any interface across which there is a change in the acoustic impedance (product of density and velocity of the material). Thus, though no energy can be refracted from the top of a low-velocity layer, a reflection does exist. Another advantage of reflection methods is the large relative amplitude of a reflection in comparison to the refraction from the same horizon. There may be a difference of as much as an order of magnitude between the amplitudes of the reflected and refracted waves. This means that smaller, non-destructive sources can be effectively used to obtain reflections from depths of several tens of metres, while it might be impossible to obtain refractions from those depths without explosive or heavy, truck-mounted seismic sources. Finally, reflection techniques have the potential of providing considerable detail about the overburden structure and bedrock topography, depending on the frequencies that can be recorded. For example, small bedrock depressions or rugged bedrock topography that would be difficult to resolve with refraction techniques, can often be more easily delineated with seismic reflection methods.

Pakiser and Warrick (1956), Warrick and Winslow (1960), and Meidev (1969) advocated the use of the reflection method in shallow engineering studies, but until the last few years it could not be widely applied. These early studies made use of either specialized high-frequency multichannel analog units or single channel recorders. Hunter and Gagne (1971) and Hunter and Hobson (1977) showed that bedrock reflections could be identified on records obtained with the refraction seismographs commonly used at that time, but resolution was poor due to the lack of high pass filters. It is only recently that low-cost seismic equipment, which allows the routine application of reflection techniques to engineering and groundwater problems, has become available. These "engineering seismographs" were initially designed for shallow refraction work, but their digital, enhancement, and filtering capabilities make them also suitable as shallow reflection instruments. At the same time, low-cost personal microcomputers have become widely available, and provide an economical means whereby reflection data collected on an engineering seismograph can be processed and displayed.

Because engineering seismographs are basically simple instruments in comparison to those used today in the oil industry, many of the sophisticated field and processing techniques developed for conventional seismic work are difficult to implement. The shallow seismic reflection methods discussed in this paper are relatively straightforward, and are equivalent to techniques developed for oil exploration 20 to 25 years ago. Yet despite this, reflection

profiling with an engineering seismograph is considered to be a new and extremely useful technique in engineering, groundwater, and placer mining studies, and has only recently been applied to such problems in North America and elsewhere.

Since the initial development of these techniques only a few years ago, there has been considerable improvement in both the recording instrumentation and the microcomputers that are available on the market. Manufacturers of engineering seismographs are now designing their instruments with the needs of both the refraction and the shallow reflection seismologist in mind. The power and speed of microcomputers are constantly being improved. The capabilities of the simple shallow reflection methods described below will undoubtedly be surpassed in the near future as full advantage of further improvements in instrumentation is taken.

FACTORS AFFECTING RESOLUTION

GROUND CONDITIONS

The successful application of any shallow reflection method depends on the detection of high-frequency energy reflected from velocity discontinuities within the overburden, or from the overburden-bedrock boundary. Although "first order" seismic theory considers the earth to be a perfectly elastic medium, in fact the real earth is a strong attenuator of high-frequency energy. For example, earthquake waves in the 0.1 to 2 Hz range can be transmitted around the world, and seismic waves in the 10 to 90 Hz range used in the oil industry are reflected from depths of thousands of metres, but energy with frequencies above 100 Hz normally have transmission path lengths of only hundreds of metres. Competent crystalline rocks support high frequencies better than poorly consolidated sedimentary rocks, while unconsolidated overburden is generally a poor transmitter of high frequencies. Unfortunately, shallow reflection methods for engineering and groundwater applications are concerned primarily with the overburden, so the ability of a particular site to transmit high frequencies is the primary concern in initial site investigations.

The optimum conditions for shallow reflection methods occur when the overburden is fine grained and water saturated; reflections with dominant frequencies of 300 to 500 Hz can be obtained from depths of more than 30 m in such field situations. These frequencies correspond to seismic wavelengths of 3 to 5 m, with a potential subsurface structural resolution of approximately 1 m. However, when the surface materials are coarse grained and dry, the dominant frequencies of reflection data can be less than 100 Hz. In such areas, seismic wavelengths may exceed 15 m, and the resolution may not be sufficient to obtain the desired subsurface information.

HIGH PASS FILTERING CAPABILITIES

The engineering seismographs on the market today all have fixed point amplifiers, and most use only eight- or ten-bit analog-to-digital (A/D) converters. This limited dynamic range is a disadvantage for shallow reflection work because the magnitude of low-frequency signals is generally so large in comparison to the high-frequency components. It is essential that instruments used for high-resolution reflection work have high pass analog filters prior to A/D conversion to offset the low pass characteristics of the earth. High pass analog filters with cutoffs ranging between 30 and 500 Hz are available on engineering seismographs at the present time. Use of these filters helps to prevent saturation of the amplifiers by low-frequency signals before sufficient high-frequency energy can be recorded. An excellent discussion of the problem of limited dynamic range and the need for high pass filters in shallow reflection work is given by Knapp and Steeples (1986a).

Besides selecting a high pass analog filter on the recording instrument, high-frequency geophones can be used to reduce some of the low-frequency components of the seismic signal. Geophones with natural resonant frequencies of 50 and 100 Hz are now commonly available, and are strongly recommended for high-resolution shallow reflection work. In many areas, the use of both high-frequency geophones and high pass analog filters can effectively remove almost all components of the seismic signal with frequencies below 100 Hz, and allow the gain to be increased so that useable frequencies up to several hundred Hz can be recorded on an engineering seismograph.

Accelerometers are an alternative to the standard geophone, whose amplitude is proportional to the velocity of the ground. For high-resolution work, accelerometers have the desirable feature that their amplitude response increases with frequency. Some excellent high-frequency reflection records have been obtained using accelerometers (e.g. Whiteley *et al.* 1986). The disadvantage of these detectors at the present time is their low output signal and high impedance. In-line amplifiers are necessary to boost the output voltage and to match the input impedance of the seismograph.

It is also recommended that single geophones be used to record each channel of shallow reflection data, as opposed to the groups of geophones which are standard in the oil industry. This is to prevent any degradation of the high-frequency components, which might be caused by the addition of signals which are slightly out of phase. The surface material in which the geophones are planted is often characterized by low velocity with considerable lateral inhomogeneity. Even slight variations in the thickness or velocity of this layer can cause differential time delays between geophones of the order of a few milliseconds, which are sufficient to adversely affect re-

flection signals above 100 Hz. Also, arrays of geophones are used primarily to attenuate surface waves, but the length of arrays that are necessary to accomplish this can cause smearing of the high-frequency components of the reflection signal because of slight changes in the angle of emergence of the upcoming energy (Ruskey 1981; Knapp and Steeples 1986b).

SOURCES

The choice of a seismic energy source can also affect the frequency of the reflected signal, and hence the resolution of the data. Many factors must be considered when selecting a source for shallow reflection surveys, including cost, convenience, portability, frequency, energy output, and safety (Knapp and Steeples 1986b).

A sledgehammer has long been used as a cheap, portable, and non-destructive source for shallow seismic surveys. Unfortunately, the energy output is limited, and the ringing of the hammer on the plate produces a ground-coupled airwave that is a major source of interference on shallow reflection records. However, in many areas a hammer can be quite sufficient as an energy source for shallow reflection work (Hunter *et al.* 1984).

Traditionally, explosives have been used for refraction surveys when a source more powerful than a hammer was required. Small explosive charges are a good source of high-frequency energy, but there are several disadvantages to the use of explosives. These include the disturbance of the ground, the cost of seismic blasting caps, and the strict regulations concerning the purchase, transport, and storage of both caps and explosives.

Over the last few years there has been considerable interest in evaluating the potential of various sources for shallow seismic surveys. Several weight drop sources have been designed and are sold commercially. Some researchers (e.g. Steeples and Knapp 1982; Seeber and Steeples 1986) have been experimenting with different caliber rifle sources for shallow reflection work. Singh (1984) has built and tested a downhole propane-oxygen detonator. A comparison of the seismic data obtained with many different sources at one particular site is given in Miller *et al.* (1986).

We have experimented with, and now routinely use, an in-hole shotgun source ("Buffalo gun") in which a shotgun shell is detonated in the ground at shallow depth. Several source tests involving "Buffalo guns", the sledgehammer, and a weight drop have been conducted (Pullan and MacAulay 1987). The results were strongly site dependent, but showed that, especially when the shotgun shell could be detonated in damp or water-saturated material, the "Buffalo gun" was an excellent, high-frequency source. With the added features of being lightweight, easily portable, and relatively inexpensive to use, it

has proved to be a very useful source for engineering seismic surveys.

DEVELOPMENT OF SHALLOW REFLECTION TECHNIQUES

At the Geological Survey of Canada we began developing and testing shallow seismic reflection methods for engineering and groundwater applications in the early 1980s, when we acquired our first digital engineering seismograph and mated it with an Apple II microcomputer (Hunter *et al.* 1982b). The original aim was to use reflection methods for mapping the overburden-bedrock interface, as the often large velocity contrast at this boundary can give rise to a prominent, easily identifiable reflection event on the seismic record (Hunter *et al.* 1982a). In many areas shallow reflection methods have also proved to be an effective means of mapping the structure within the overburden.

From the beginning we have attempted to develop methods which can be implemented with a minimum investment in equipment and computing capabilities. The objective has been to make the application of shallow reflection techniques possible for a small engineering geophysics company. Thus, we attempt to use equipment that would be readily available to such a company, and to keep specialized hardware and data processing requirements to a minimum.

Several other groups have also been involved in the development of shallow reflection techniques, notably those at the Kansas Geological Survey and the University of Utrecht in the Netherlands. Both these groups have taken a rather different approach to that described in this paper, and have adapted standard common-depth-point (CDP) data acquisition and processing techniques for high-resolution shallow reflection applications. CDP techniques are well established in the oil industry, and are an effective means of improving the signal/noise ratio. The disadvantage is that they require considerable computing capabilities.

The group at the Kansas Geological Survey uses a conventional seismic recording system with a high sampling rate, and processes the data on a main-frame computer. They have experimented extensively with rifle sources for high-resolution work, and have had considerable success in obtaining shallow reflections under a variety of geological conditions (Steeple and Knapp 1982; Steeples 1984; Seiber and Steeples 1986; Steeples *et al.* 1986). In an attempt to make shallow CDP surveys cost-effective for engineering or groundwater applications, they have made significant progress in improving the efficiency of the field work, but data processing costs have still been about twice the cost of data acquisition (Steeple *et al.* 1985; Steeples and Miller 1986). To reduce the high processing costs, this

group has recently implemented in-field processing on a microcomputer (Somanas *et al.* 1987).

A group headed by K. Helbig at the University of Utrecht has been using an engineering seismograph and software developed in-house to collect and process CDP data from tidal flats in the Netherlands. The tidal flats are near-ideal areas for obtaining high-frequency data, because the sediments are completely water saturated and no attenuating low-velocity surface layer exists (Herber *et al.* 1981). Excellent high-frequency seismic sections with a resolution of 0.5 m and reflections from as shallow as 5 m have been produced by this group (Helbig *et al.* 1985; Jongerius *et al.* 1985).

As computing costs decrease and software packages for CDP processing of shallow reflection data become more readily available, CDP surveys will eventually be cost-effective for engineering and groundwater applications. We are at the beginning of this transition period now, with several software packages for microcomputers coming onto the market in late 1987 (Somanas *et al.* 1987; McGaughey *et al.* 1986). Meanwhile, much useful shallow reflection surveying can be carried out using the simpler and cheaper techniques described below.

CONCEPT OF THE "OPTIMUM WINDOW"

The methods developed at the Geological Survey of Canada are based on the concept of the "optimum window". The "optimum window" is the range of source-receiver separations which allows the reflectors to be observed with minimum interference from signal generated noise.

Figure 56.1 shows a composite field seismogram from a site near Winkler, Manitoba, where 45 m of unconsolidated overburden overlies a Cretaceous shale. At near normal incidence (i.e. at small source-receiver separations), the bedrock reflector disappears in a zone of high noise. This noise consists of ground roll (Rayleigh and surface modes) and a ground-coupled airwave which is often present with hammer, weight drop, or poorly tamped explosive sources. In many cases the ground roll consists predominantly of low-frequency energy, and high pass filtering and the use of high-frequency geophones can reduce this interference. The airwave, however, is usually a broad-band signal, and cannot be reduced substantially by filtering.

The near side of the "optimum window" is governed by the relative positions in time of the bedrock reflector and the onset of interference from low-velocity noise. The deeper the target horizon, the greater the source-receiver separation required to observe the reflector before the arrival of the airwave and/or groundroll. The far side of the "optimum window" can be more difficult to determine. It is dependent on such factors as the frequency of the data, interference of the bedrock reflector with shallow reflectors from within the overburden, phase

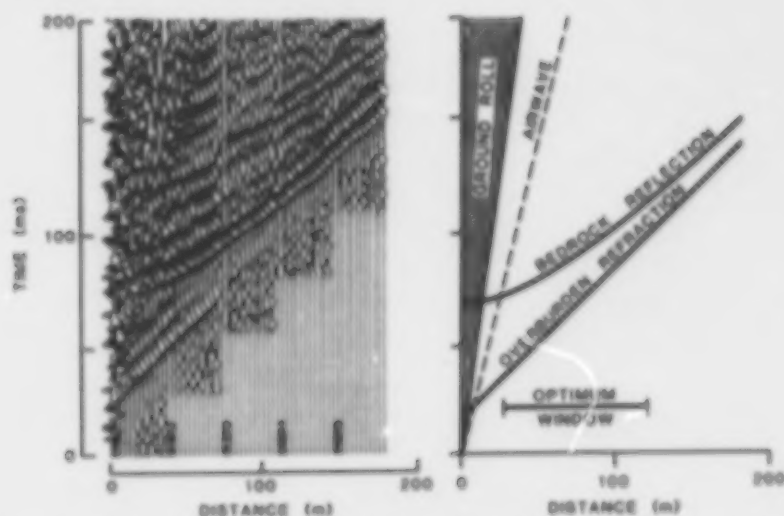


Figure 56.1. Composite shallow reflection record from Winkler, Manitoba (left), and the corresponding time-distance plot (right) identifying the major seismic events on the record. The "optimum window" is that range of source-receiver separations which allows the target reflector to be observed without interference from other events.

and amplitude changes in the wavelet reflected from the target horizon, and finally, the objectives of the particular survey.

The occurrence of shallow reflectors within the overburden can limit the far side of the "optimum window" in cases where these events merge with the bedrock or target reflector. This will, of course, depend on the frequency of the reflection data. Merging or interfering of the reflectors will become a problem at smaller source-receiver separations for lower-frequency data.

The far side of the "optimum window" can be governed by loss of correlation of the reflection signal due to amplitude and phase changes that are a function of the distance between source and geophone. These changes are associated with the critical angles dictated by compressional and shear wave velocity contrasts across the reflection boundary. This subject is discussed in detail in Pullan and Hunter (1985), where it is concluded that, in general, the reflected signal is not substantially altered so long as the source-receiver separation does not exceed the depth to bedrock.

The object of the survey may also affect the choice of the source-receiver geometry. If the aim is to obtain a single depth point determination to a particular reflector, then the reflector should be observed over as large a range of source-geophone distances as possible, in order to obtain the best estimate of average velocity down to the reflecting horizon. If, on the other hand, the aim is to produce a seismic section from a series of shallow reflection records collected along a line, then the spacing of the traces within the optimum window will be deter-

mined in part by the desired subsurface coverage, and in part by the degree of normal moveout (NMO) stretching of the near-surface events during processing which is acceptable.

Our first shallow seismic reflection surveys were carried out in this manner, using the "optimum window" technique (Hunter *et al.* 1982a, 1982b, 1984). The advantage of this technique is that the field work can be carried out quickly and efficiently. However, the requirement for an accurate velocity-depth function is often difficult to meet, especially for the upper part of the section where lateral inhomogeneities may be significant. Additional disadvantages are the differential stretching in time of the shallow wide-angle events by the NMO corrections, and the difficulty in making adequate static corrections for velocity or thickness variations in the layer above the water table. Thus, though the "optimum window" technique can be an effective means of following a single target reflector (such as the top of bedrock), it is generally not very useful in resolving details of the structure within the overburden.

THE "OPTIMUM OFFSET" TECHNIQUE

The "optimum offset" method was developed in an attempt to overcome the above-mentioned shortcomings of the "optimum window" technique. This method provides for better resolution of shallow reflections from within the overburden. The field data acquisition component of the "optimum offset" method is less efficient than for the "optimum window" technique; however, the data processing is much simpler and less time consuming.

DATA ACQUISITION

Initial expanding spreads must be shot around the survey area to determine the "optimum window". From within this window, one particular source-receiver separation is chosen, such that the target reflector can be observed without interference throughout the area of interest. This choice is a critical one, since once the "optimum offset" is selected, it should be maintained for the entire seismic line. Each channel of the "optimum offset" record is recorded individually by shooting into each geophone in turn from the selected offset (Figure 56.2).

As long as the chosen offset is within the "optimum window", there is complete freedom to select the geophone spacing based on the desired subsurface coverage. In most of the examples shown in this paper, a geophone spacing of 3 m has been used. We have found this, or even finer, spacing to be most effective when the object of the survey is to map detailed structure within the overburden or on the bedrock surface. Spacings of 5 m or more can be used when a more regional picture of subsurface structure is desired.

The "optimum offset" method requires a seismograph with the capability of holding individual traces in memory while recording other channels. Most engineering seismographs on the market today have this "memory freeze" or "channel locking" feature. It is possible to use a single channel instrument to collect "optimum offset" data, but multichannel seismographs are strongly recommended. When viewing only one channel at a time, it is easy for an operator to become confused as to the location in time of the target reflector. However, multichannel seismographs allow the operator to continually verify that a particular pulse on a trace is a reflection, by viewing its relation to other events on the seismogram. For example, an airwave will produce a flat-lying event on an "optimum offset" record, which could easily be mistaken for a reflector. However, on a multichannel record, the airwave can be immediately identified on the basis of its low velocity.

For each geophone spread, it is recommended that two multichannel records be obtained in addition

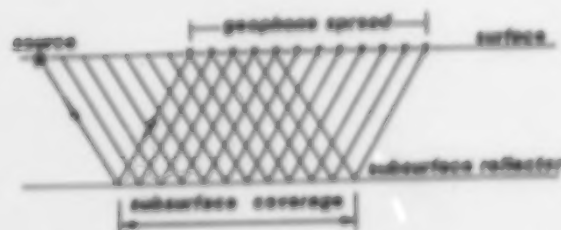


Figure 56.2. Diagram showing the setup for recording an "optimum offset" record, and the reflection ray path for each of the shots required.

tion to the "optimum offset" record. First, a standard refraction record should be shot with the source close to the end of the array. This is to obtain velocity information for the surface layer, and an estimate of the depth to the water table. Secondly, a multichannel reflection record should be recorded, preferably with the source positioned so that the "optimum offset" is near the midpoint of the geophone spread. These records may be used later for velocity analysis. Alternatively, after the "optimum offset" section has been shot, the operator may select locations along the survey line where the section indicates that the stratigraphy is relatively flat-lying, and return to these sites to shoot multichannel records to be used for velocity analysis.

DATA PROCESSING

The data processing required to produce a final "optimum offset" seismic reflection section is shown in flowchart form in Figure 56.3. The processing is largely cosmetic, and a preliminary section can easily be produced in the field office on the day the data are collected. The data are first transferred from the seismograph to an Apple II+ or IIe microcomputer, and stored on floppy disk. Transfer routines are available commercially for all the engineering seismographs on the market at the present time. Processing software has been developed for the Apple microcomputer with two disk drives, and an Epson wide-track, dot matrix printer (Norminton and Pullan 1985, 1986).

PROCESSING OF "OPTIMUM OFFSET" DATA

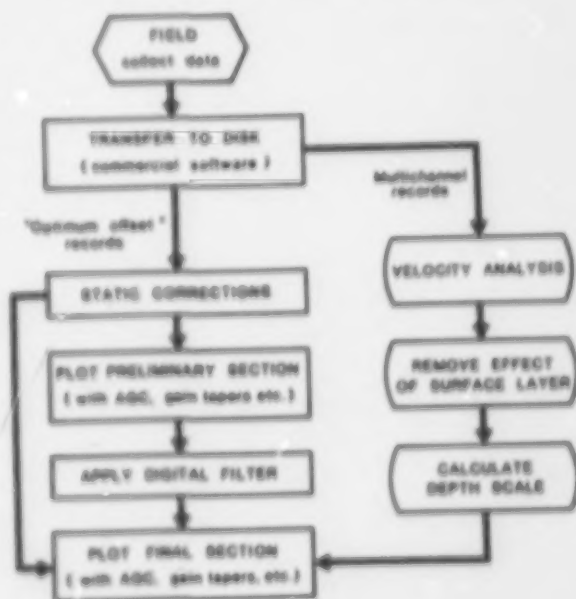


Figure 56.3. Flowchart showing the processing steps leading to a final "optimum offset" section. See description in text.

The first step in the processing sequence is the application of static corrections to each trace of the "optimum offset" record. In most cases, the first arrival event on each trace is the refraction from the top of the water table. Hence, by aligning the first arrivals the effect of the variable low-velocity layer above the water table can be removed.

The "optimum offset" section is produced by plotting the statically corrected "optimum offset" records with an automatic gain control (AGC) to normalize trace-to-trace amplitudes and to enhance weak reflectors, and linear gain tapers to enhance the amplitudes of target reflectors. Digital bandpass filtering of the data can be applied to improve and standardize the frequency spectra of the records.

Once the "optimum offset" section has been plotted, it is necessary to determine a velocity-depth function which can be used to calculate a depth scale corresponding to the two-way travel time of the section. Reflection events on the multichannel reflection records which were shot along with the "optimum offset" records are analysed to obtain estimates of the average velocity between the surface and the reflector. It is recommended that an average velocity-depth function be estimated from as many reflection events as possible within one segment of a survey line. The average velocities must be corrected for the effect of the low-velocity layer at the surface. The thickness and velocity of this layer are calculated from the refraction record from each spread. The depth scale computed for the section will be non-linear, particularly near the surface, because of the non-zero source-geophone offset.

PROS AND CONS

The major disadvantage of the "optimum offset" technique is the time required to take individual

shots for each trace of the final section. However, with a three- or four-man crew working along roads from a truck, we have found it realistic to expect to cover 500 m per day with a geophone spacing of 3 m. The actual production varies, of course, depending on the site conditions, and particularly on the possible requirement for stacking shots to improve the signal-to-noise ratio.

The advantages of the method are the simplicity of the data processing, and the fact that no NMO corrections are required so that there is no differential stretching or distortion of wide-angle near-surface reflections. The "optimum offset" technique allows the user to quickly obtain a picture of the structure of the overburden and of the topography of the bedrock surface, without having to first determine the velocity structure. Preliminary sections can be prepared on site in the field office within hours of collecting the data.

EXAMPLE "OPTIMUM OFFSET" SHALLOW REFLECTION SECTIONS

Over the last few years we have collected "optimum offset" data from a wide variety of geological settings - Precambrian to Tertiary bedrock, overburden thicknesses from 15 to 400 m, and a spectrum of overburden types ranging from recent marine clays to glacial tills. The example sections described below were chosen to illustrate some of the capabilities and limitations of the "optimum offset" technique. All sections were shot using a 12-gauge "Buffalo gun" as the seismic source.

BEDROCK TOPOGRAPHY

Figure 56.4 is a 400 m section of an "optimum offset" profile from Val Gagné, Ontario, which shows a buried bedrock valley (Pullan *et al.* 1987). This sec-

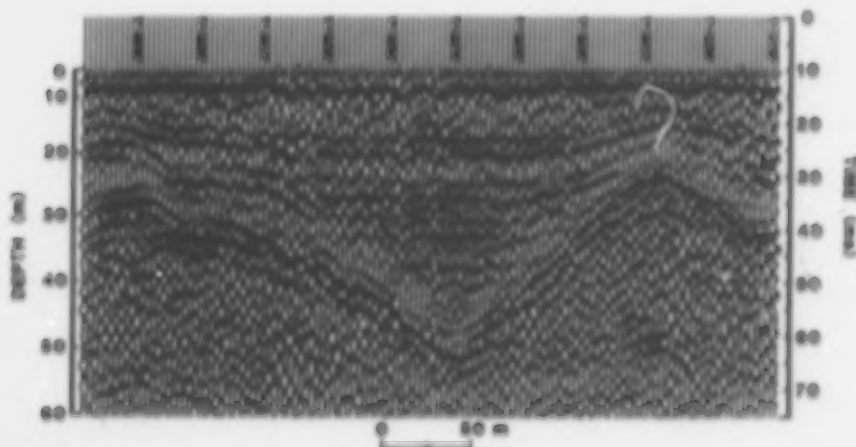


Figure 56.4. "Optimum offset" shallow reflection section from Val Gagné, Ontario, illustrating the potential of the technique for mapping fairly rugged subsurface structure.

tion demonstrates the potential of the "optimum offset" shallow reflection method for mapping fairly rugged subsurface structure. This buried valley is 200 m wide, and the maximum relief on the bedrock surface is approximately 25 m.

Within the overburden there are several reflectors which are almost flat-lying. Based on the logs of nearby drillholes, the overburden is thought to be essentially a clay unit. The reflectors within this unit appear to be draped over the bedrock topography, that is, they dip gently towards the centre of the bedrock valley and are arched up over the bedrock highs. This is attributed to dewatering and compaction of the clays after deposition.

This section was shot with an "optimum offset" of 21 m, and a geophone separation of 3 m. The data were filtered in the field by the use of 100 Hz geophones, and a 300 Hz high pass analog filter on the seismograph. Prior to final plotting, a digital bandpass filter from 300 to 800 Hz was also applied. The reflection signals on this section have a dominant frequency of approximately 300 Hz. This is an excellent site for shallow reflection work; the surface materials are fine grained and the water table is within 1 m of the surface.

SHALLOW RESOLUTION

Figure 56.5 is a 430 m section of an "optimum offset" profile from Casselman, Ontario, which is shown to illustrate the shallow high resolution potential of the technique.

Bedrock at this site is a massive Paleozoic limestone which dips gently to the north (left to right on the section). Several continuous reflectors can be observed within the overburden, and they correlate well with the lithologic boundaries identified in a borehole that was later drilled on the line by the Ontario Ministry of Natural Resources. The upper 15 m of the section consists of fine sand with clay layers. Beneath this is a clay unit in which the sand

content increases with depth. A thin layer of till overlies bedrock, and was encountered in the drillhole at a depth of 28 m.

With the geophones and the shotgun source planted in the fine-grained, water-saturated sediments at this site, no airwave was observed on the records. Ground roll was also drastically reduced by the use of 100 Hz geophones and the 300 Hz high pass analog filter on the seismograph. Thus, it was possible to shoot this section with an "optimum offset" of only 12 m. This, and the fact that at this site the dominant frequency of the reflected signals is close to 500 Hz, means that it is possible to resolve the overburden structure to within 10 m of the surface. This section is an example of the excellent, high-resolution data that can be obtained under the best field conditions.

THICK OVERBURDEN

Figure 56.6 is a short section of an "optimum offset" line that was shot in the Okanagan Valley near Vernon, British Columbia, in an attempt to map deep aquifers used for irrigation. It is shown here as an example of the depth of penetration that is potentially possible with this simple reflection technique. Penetration of over 400 m was achieved at this site.

When these records were collected, the water table was approximately 5 m below surface, and the shot was well above this in a hard-packed dry silt. The record quality was improved when a water tamp was used in the shot hole, but a ground-coupled airwave could still be observed on some of the records, and an "optimum offset" of 150 m had to be selected in order to allow a sufficient noise-free recording window. The dominant frequencies of the reflected signals were between 80 and 100 Hz, and in order to record these, 50 Hz geophones were used with the analog filters on the seismograph set for a bandpass centred at 100 Hz. The geophone separation was 3 m.

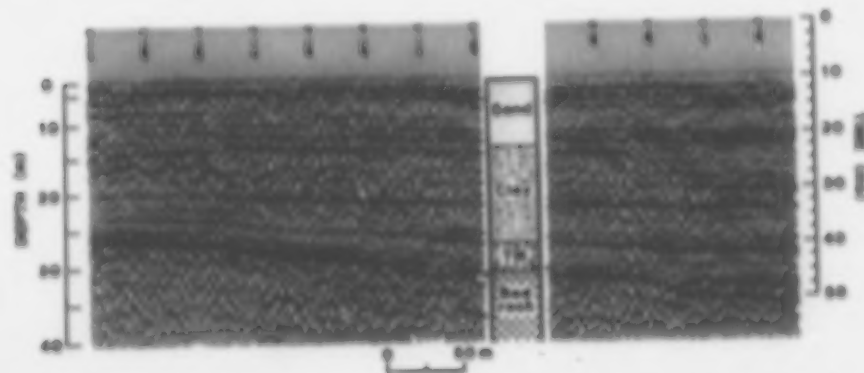


Figure 56.5. "Optimum offset" shallow reflection section from Casselman, Ontario, showing the high-resolution potential of the technique.

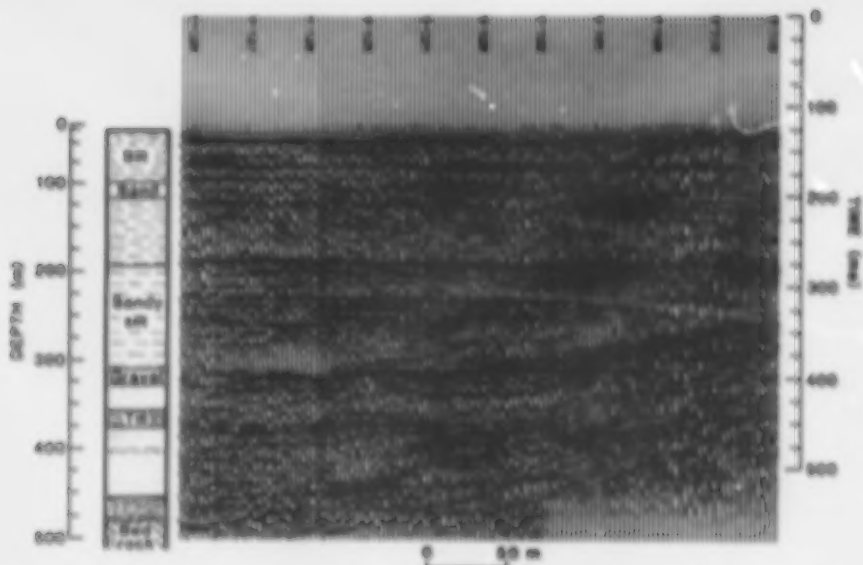


Figure 56.6. "Optimum offset" shallow reflection section from Vernon, British Columbia, illustrating the depth of penetration it is possible to achieve in areas of thick overburden.

The section shows over 200 m of relatively flat-lying proglacial lacustrine sediments overlying an unconformable horizon which corresponds to the top of coarse-grained sands and gravels within which the aquifers are found. This stratigraphic interpretation of the data is based on a borehole which was 100 m off-line at the left side of the section. The sands and gravels have been tentatively interpreted as Quaternary in age, although the possibility exists that they may be as old as Tertiary. Bedrock definition beneath the aquifer sediments, and bedding definition within the aquifer zones is poor, probably as a result of the high acoustic impedance contrast at the unconformity and the presence of diffractive events below that.

OVERBURDEN STRUCTURE

Figure 56.7 is a 330 m section of an "optimum offset" profile from Val Gagné, Ontario, which demonstrates that the "optimum offset" technique can be used as a tool for mapping the structure of the overburden. This section was shot as part of a program to test the feasibility of using shallow reflection techniques to delineate occurrences of glacial till beneath varying thicknesses of fine-grained sediments (Pulian *et al.* 1987).

The "optimum offset" used for this line was 30 m, and the spacing between 50 Hz geophones was 2.5 m. The data were filtered in the field with a 300 Hz high pass analog filter on the seismograph, and a digital bandpass filter from 300 to 800 Hz was applied before the final section was produced. The near-surface material at this site was fine grained

and water saturated, and excellent resolution of the subsurface structure was obtained.

Based on the seismic results, the Ontario Geological Survey drilled a hole to sample a pocket of glacial till which was identified on the reflection section. The borehole log is shown on the figure. The essentially flat-lying upper section of the overburden consists of clay grading into a thick sand unit. A contact between massive and varved clay occurs at a depth of 17 m, and this interface is clearly visible on the seismic section at a time of approximately 30 ms. The top of the sand is an indistinct boundary and is not easy to define on the seismic section. However, a reflector correlates well with the interface between a fine and coarse sand at a depth of approximately 50 m. At the drillhole, 15 m of sandy till overlies bedrock. The section indicates that the till is a small pocket with a lateral extent of approximately 100 m. This example clearly demonstrates the potential of the "optimum offset" technique for mapping detailed structure of the overburden.

A second example is shown in Figure 56.8, a high resolution section from a suburban area of the Fraser Delta, British Columbia. These records were shot with an "optimum offset" of 12 m, and a geophone spacing of 1.5 m, to look specifically at details of the shallow structure of the overburden. The section is 270 m in length. The source and the 100 Hz geophones were planted in the bottom of water-filled irrigation ditches for optimum coupling. The two groups of dead traces on the right side of the section mark the position of a paved access road where it was impossible to place either the

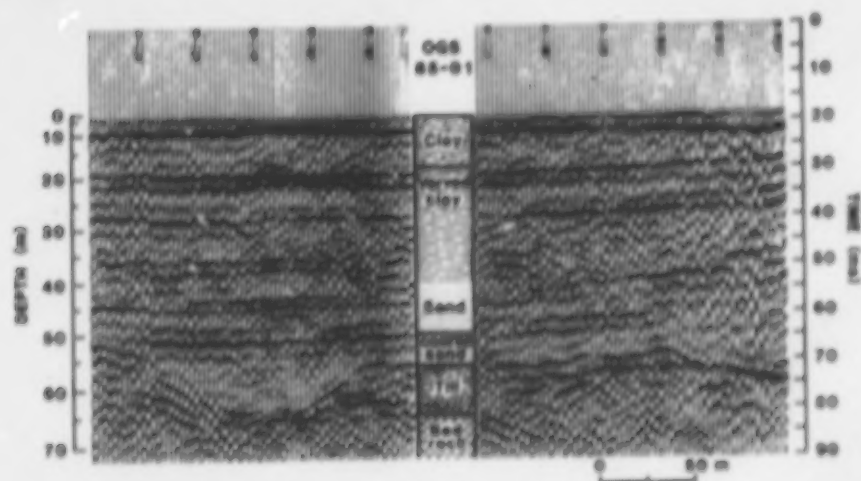


Figure 56.7. "Optimum offset" shallow reflection section from Val Gagné, Ontario, which demonstrates that the technique can be used for mapping the structure of the overburden.

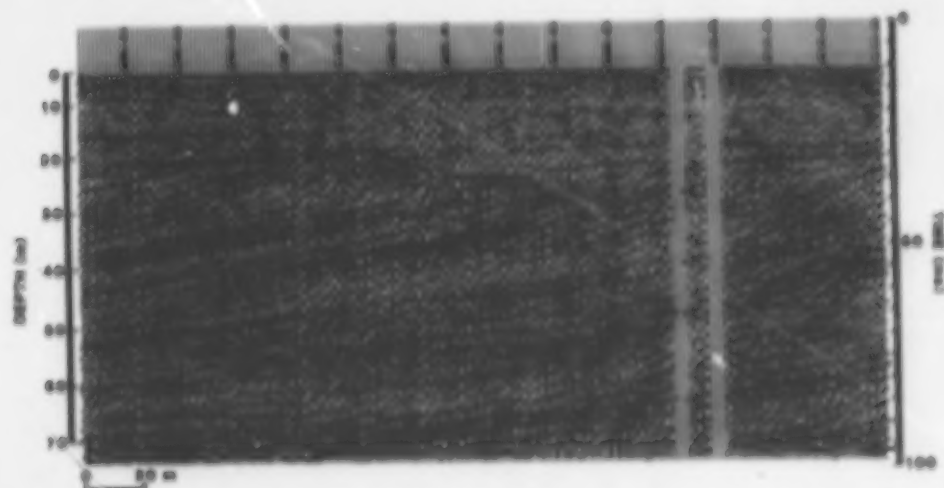


Figure 56.8. "Optimum offset" shallow reflection section from Fraser Delta, British Columbia, detailing the shallow structure of the overburden.

geophones or the source. The data were filtered in the seismograph with an analog bandpass filter from 350 to 1000 Hz. This is an example of excellent high-resolution data; the reflection energy on the section has a dominant frequency of 500 Hz, corresponding to wavelengths of approximately 3 m.

This section shows an unconformity between the flat-lying recent delta deposits at the surface and a sequence of older Quaternary foreset beds below. The modern sediments are approximately 20 m thick, except in a shallow channel cut just to the right of the centre of the figure, where they reach a thickness of 25 m. Adjacent drillholes suggest that

the foreset beds are composed almost entirely of sand. Hence, the dipping reflectors are derived from constructive interference from minor density and velocity variations within the sand.

FOUR SECTION

As discussed above, the successful application of any shallow reflection method depends on the detection of high-frequency energy reflected from the target horizon. Some sites, particularly those where the surface materials are coarse grained and dry, are unfavourable in this regard. An example is shown in Figure 56.9, which is a 200 m section of an "optimum offset" profile from Wandering River, Alberta.

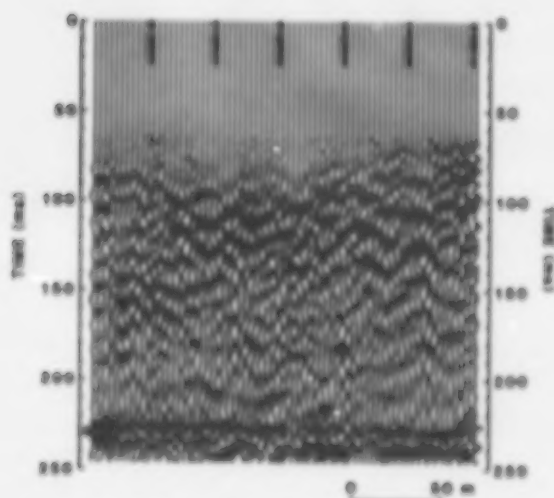


Figure 36.9. Example of an area where the "optimum offset" shallow reflection technique does not work. The only correlatable event on the section is the airwave which arrives at a time of approximately 225 ms.

This is a site where the shallow reflection methods discussed in this paper do not work.

From drilling in the area it is known that bedrock is a siltstone overlain by thick sequences of tills and gravels. At this particular site bedrock is estimated to be approximately 70 m below surface. It was expected that the bedrock reflection might not be large in amplitude because of the low velocity contrast at the overburden/bedrock interface.

However, the major problem in this area was the very poor transmission of high-frequency seismic energy. The dominant frequency of the records shown in Figure 36.9 is approximately 50 Hz, and this is due to the use of 50 Hz geophones and a high pass analog filter of 100 Hz on the seismograph. The records are characterized by a series of low-frequency rolls with large static variations from trace-to-trace (no static corrections have been made in this plot). The only correlatable event on the section is the airwave, which with the chosen "optimum offset" of 75 m, arrives at a time of approximately 225 ms.

The poor results obtained at this site are attributed to very high attenuation in the low-velocity surface layer (above the water table). The attenuation of high frequencies is particularly severe, but even the energy return in the 50 Hz range was very poor, requiring the amplifiers on the seismograph to be set at maximum gain. One way it might be possible to overcome this problem would be to drill deeper shot holes and geophone holes, so that the source and the receivers could be planted at or below the water table. However, this would require specialized

equipment, and would certainly slow down production and increase the cost of the survey.

SUMMARY

In the past ten years the development of low-cost digital engineering seismographs and microcomputers has led to the introduction of high-resolution seismic reflection techniques to engineering and groundwater studies. Not unlike other geophysical techniques, the successful application of the "optimum offset" shallow reflection method discussed in this paper is site-dependent. However, when ground conditions are favourable, the method can provide resolution of the bedrock topography and of the structure within the overburden on a scale not hitherto available. Since its development, the authors have successfully tested the applicability of the "optimum offset" method in a variety of geological settings in Canada. We hope that the next ten years will see its widespread acceptance and application by the international community of engineering and groundwater geoscientists.

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57. Freshwater-bearing Sandy Creekbeds Explored by Electromagnetic Measurements in a Mainly Saline Coastal Area of the Netherlands

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ABSTRACT

In recent geological and historical time, the land that today comprises the province of Zeeland (in the southwestern part of the Netherlands) was frequently invaded by the sea. Consequently, the groundwater is saline in most parts of the area. Erosion by recent marine transgressions created gullies (creeks) which were later infilled with sands. Rainwater infiltrated these sandy creekbeds, thus creating freshwater lenses. These freshwater aquifers are very small but of interest for local agriculture.

Electromagnetic measurement is an ideal tool for exploring small freshwater lenses because the method is fast and cheap, allowing a dense grid of observation points. A regional EM survey was carried out in Zeeland, measuring approximately one station per km². Once the low conductivity zones had been delineated by EM, only a limited number of geo-electrical Schlumberger soundings at selected sites were needed to establish the vertical layer sequence (thickness of the aquifer). At some locations, geophysical well logs were made in exploratory boreholes to check the results.

In this paper the results of part of the survey are presented and the problems related to electromagnetic measurements in highly conductive saline areas are discussed.

THE AREA AND THE PROBLEM

Zeeland, a province in the southwestern corner of the Netherlands (Figure 57.1), originally consisted of a group of islands, separated by large estuaries. In the past, the area was invaded frequently by the tempestuous North Sea, but after the last big flood in 1953, which devastated much of Zeeland, the Delta Project was taken on, sealing most of the sea-arms by dams; and thus lessening the risk of floods. In one estuary, instead of a dam, a storm-surge barrier has been built; this remains open most of the time, thus preserving the estuarine environment and commercial fishery. It is only closed during dangerous storms. The Delta Project, which was completed in 1966, leaves open the southernmost estuary, the Westerschelde, which connects the Belgian port of Antwerp to the sea.

The formation of Zeeland has been governed by the sea not only in recent historical periods, but also

during geological time. Almost all of the Tertiary and Quaternary sediments, mainly clays and sands, have been deposited in marine environments, where changes in the sea level relative to land determined the type of sedimentation. As a consequence, the water in these formations is mostly saline. In most parts of the area, near-surface clay and peat layers, (generally no thicker than a few metres), prevent rainwater from infiltrating deeper aquifers. However, during recent periods of transgression, erosion has occurred, forming tidal gullies or creeks where clays and peat were removed. These erosion channels, which cut into older formations up to depths of several tens of metres, were later infilled by medium- to fine-grained sands (Figure 57.2). The subsequent settlement of the adjacent clays has caused the sandy creekbeds to form slightly elevated topographic features in the actual landscape, called creek ridges. Owing to the absence of clays and peat and the elevated position, precipitation infiltrates the sandy creekbeds and pushes the saline water away, thus creating freshwater reservoirs.

These groundwater reservoirs, though limited in size both laterally and vertically, and only replenished by direct precipitation, constitute important reserves for local agriculture, which is one of the major economic activities of Zeeland's population. In periods of drought, most farmers do not suffer, because the extensive shallow clay layers keep the moisture in the topsoils. However, it is precisely the agriculture practiced on the higher sandy soils of the creeks that encounters problems in dry periods when water tables decline and any occasional rain instantly infiltrates deep into the permeable ground. It is therefore a quirk of nature that it is these sandy creekbeds that constitute practically the only aquifers where freshwater may be found. Thus, irrigation by groundwater abstracted from shallow wells or drainage systems is feasible. Also, if the stored volumes are too small to meet demand, or if upconing of saline water becomes a threat, artificial infiltration of surplus water in rainy periods might even be considered.

Below, the exploration of freshwater-bearing creekbeds in the southernmost part of Zeeland is recounted. This area, called Zeeuws-Vlaanderen, lies south of the open Westerschelde estuary and adjacent the Belgian border (see Figure 57.1). Near this border, neither shallow peat nor clays have been de-

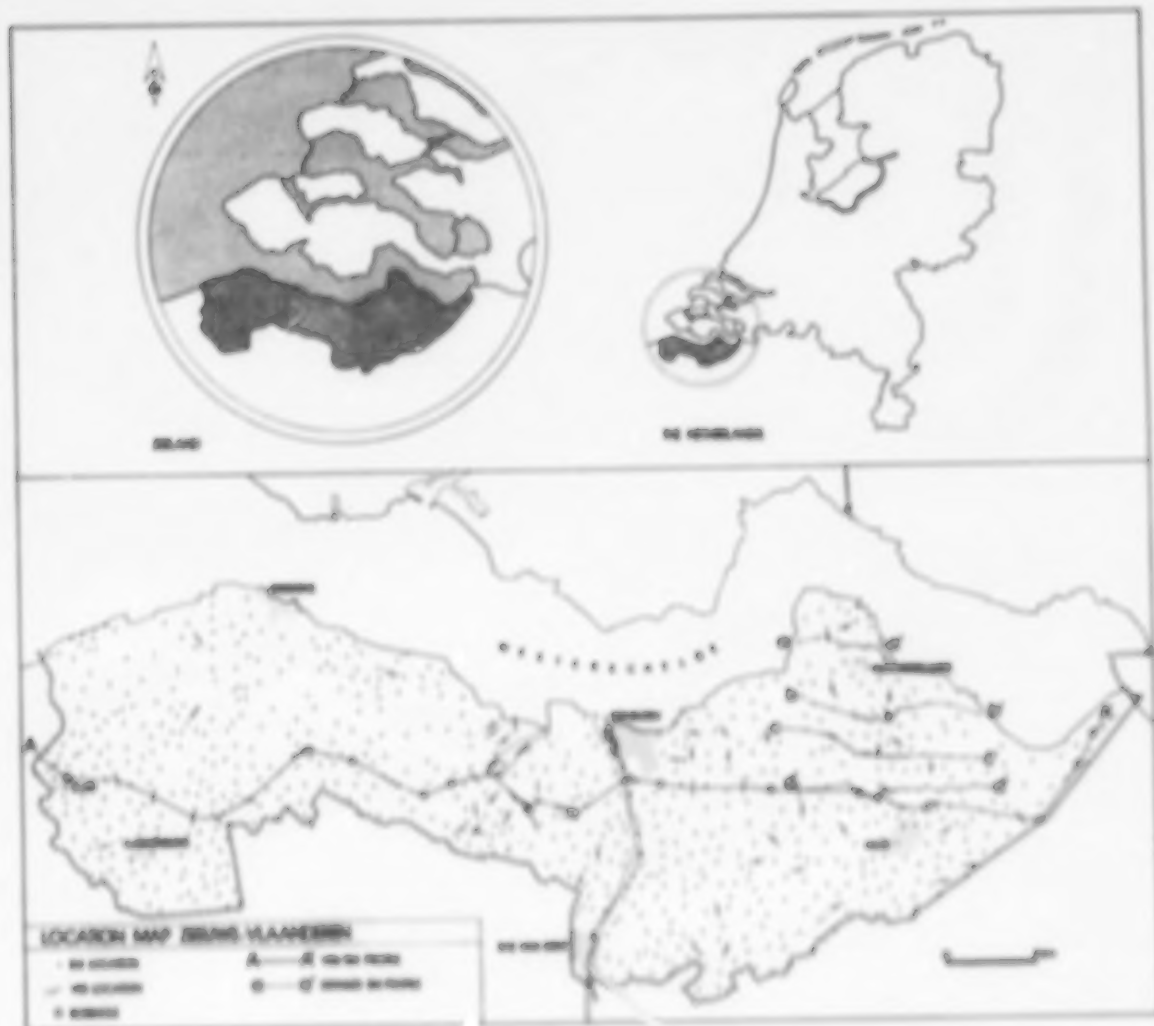


Figure 57.1. Location map.

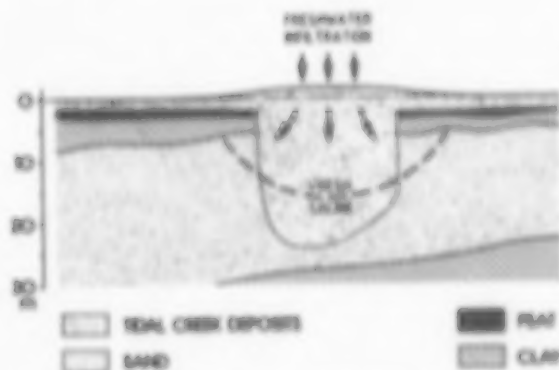


Figure 57.2. Schematic geological cross-section through an infilled sandy creekbed, and the creation of freshwater lenses.

positioned; nor were tidal gullies formed, because recent transgressions did not reach this slightly more elevated zone. Instead, this strip along the border is covered by aeolian sands, formed during the last glacial period; like the sandy creekbeds, these cover sands constitute favourable zones for rainwater infiltration.

THE TOOLS APPLIED

The infilled sandy creekbeds have been mapped in detail by the Netherlands Geological Survey. However, the water is not fresh everywhere in the sandy creekbeds, and neither is freshwater solely confined to gully structures. If use is to be made of the freshwater reserves and the repercussions of water abstraction are to be assessed, then these reservoirs need to be delineated with great precision. Geophysical exploration techniques are extremely suit-

able for this purpose. The application of geophysics to water salinity problems is certainly not new. Over 20 years ago, geo-electrical methods were being used with great success to establish the distribution of fresh, brackish, and saline groundwater in coastal areas of the Netherlands and Belgium (Van Dam and Van Rummelen 1960; Walter 1963; De Brueck and De Moor 1962). However, the small dimensions of the sandy creekbeds, their irregular pattern, and the detailed delineation desired, require a more efficient approach, allowing a large number of measurements to be made in a short time and at a low cost.

The electromagnetic method satisfies these requirements, and was therefore selected to be the major geophysical tool for the shallow groundwater exploration in Zeeland carried out by TNO-DGV Institute of Applied Geoscience. The electromagnetic measurements were made with EM34-3 equipment of Geonics Limited which has the following major advantages (McNeill 1980a):

- simple and fast operation
- direct reading of electrical conductivity values
- depth range sufficiently large for shallow surveys like the one in Zeeland

However, EM34-3 measurements do not lend themselves easily for quantitative interpretation, especially not in saline areas where the instrument's constraints of operating at low induction numbers (McNeill 1980a) are not satisfied. For this reason, a number of geo-electrical soundings at selected sites were incorporated into the investigation. These soundings were made with TNO's GEA-51 direct-current instruments.

In order to verify the results of the EM survey, several test holes were made, in which geophysical well logs were run, using TNO-DGV B-250 equipment.

THE ELECTROMAGNETIC SURVEY

In Zeeland, a regional EM survey was carried out, measuring approximately one station per km²; 783 stations were more or less uniformly distributed across Zeewo-Vlaanderen (see Figure 37.1). At each location, readings were taken with both vertical and horizontal coil orientation at the three possible intercoil spacings of 10, 20, and 40 m. An average of 40 locations were measured daily.

Thus, in a short time, a large amount of field data were obtained (8 x 783 readings) which had to be processed efficiently, if the method's major advantage of speed was to be maintained. For this purpose we used a computer program (EMDataSys), running on a PC under MS-DOS. This program was developed at TNO-DGV Institute of Applied Geoscience to store, process, and present EM data on maps or in profiles. A general flowchart of the procedure is shown in Figure 37.3. It is extremely useful

to computer-plot the observed EM values during the preliminary interpretation. This was also done for the final report, plotting EM location points and values directly on topographic maps. Although contour programs are available, manual interpolation is still preferred for the most part. On the maps or in the profiles, either the actually observed conductivity values or the reciprocal resistivity values may be plotted. Water geophysicists often prefer the latter, as it facilitates the correlation with geo-electrical data. Before converting conductivities into resistivities, the program first automatically corrects for any deviations that arise at high values of terrain conductivity when the instrument output is no longer proportional to the actual conductivity (McNeill 1980b). The main results of the EM survey in Zeewo-Vlaanderen were the contour maps of apparent resistivity, obtained from measurements with

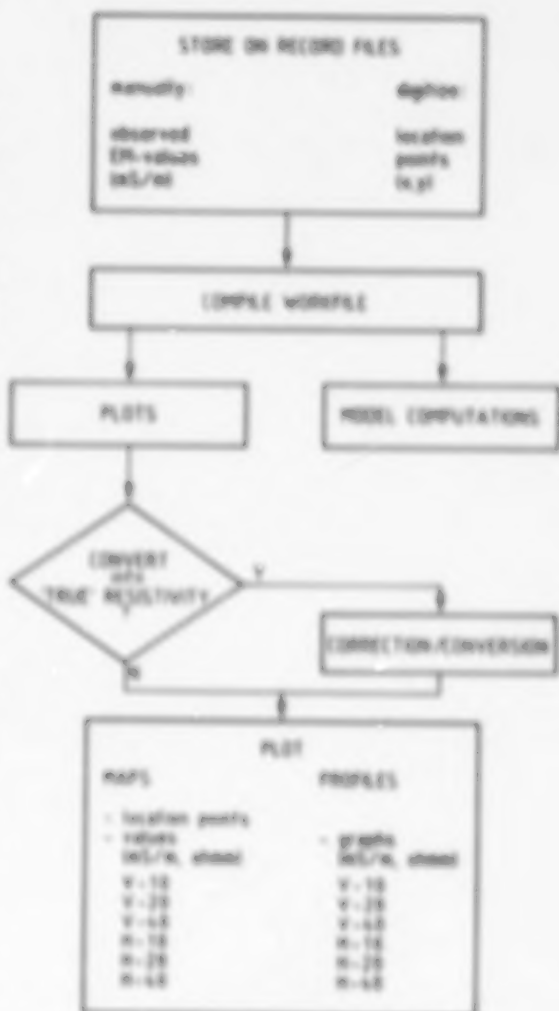


Figure 37.3. General flowchart of EM data processing.

vertical coils (horizontal dipoles) spaced at 10, 20, and 40 m (Figure 57.4). Similar maps were made for the observations made with horizontal coils (vertical dipoles). However, these data are less reliable, not only because of possible coil misalignments, but especially because the very high conductivities of the saline layers produce erroneous instrument readings (against which even the correction graph (McNeill 1980b) is powerless), or meter readings that go off-scale. Nevertheless, the maps of H-10 and H-20 resemble those of V-20 and V-40 respectively, but consequently do not provide any additional information. At only a few places could measurements be made with horizontal coils at 40 m; this indicates that at the corresponding penetration depth all terrain conductivities are extremely high.

The contour interval of the maps, chosen more or less at random, is further explained in the last section of this paper. The zones with the highest apparent resistivities (25 ohm-m or more), which presumably indicate the most promising areas for fresh groundwater, do indeed reflect gully patterns, except in parts along the southern border, where regions of relatively high resistivity are more extensive. These latter areas are infiltration zones formed by cover sands.

The most striking picture of the EM anomalies is given by the map of V-10 measurements, which has the smallest penetration depth. With increasing intercoil spacing, (thus with increasing depth), the lateral extent of the high resistivity zones diminishes, pointing to increasing ground conductivity and denoting the limited thickness of potential freshwater volumes. Along large parts of the southern border, however, high resistivities do remain visible at 40 m intercoil spacings. This is because of the absence of saline water. Instead, the base of the freshwater-bearing cover-sand aquifer is formed by a thick layer of massive clays found at shallow depth, as explained in the section dealing with the geo-electrical survey. Although these clays do have low resistivities, their values are not nearly as low as those of sands saturated with saline water.

The zones of high apparent resistivities delineated by the V-10 measurements were superimposed on the geological map (Van Rummen 1963) showing the distribution of the thin peat layers in the shallow *subsoil* of Zeewoed-Vlaanderen (Figure 57.1). It should be noted that in many parts, high resistivities are found where peat is absent, having been removed by tidal erosion. This supports the expected relationship between freshwater occurrences and sandy creekbeds, because no substantial anomaly would have been found if these infilled creekbeds still contained saline water.

The work described above only resulted in establishing the lateral distribution of apparent ground resistivities: the water quality or the volumes of freshwater involved were still unknown, and yet it is

this information the hydrogeologist expects to be provided with. To remedy this, the EM reconnaissance survey was extended as follows:

1. The presumed correlation between EM values and freshwater occurrences was verified by test drilling.
2. Geo-electrical soundings were made at selected sites, to determine the thickness of the aquifers.
3. Empirical relations between EM values and water salinity and aquifer thickness were tentatively sought, in an attempt to translate the geophysical maps into hydrogeological ones.

TEST DRILLING

The most conspicuous gully pattern, the one between Hult and Kloosterzande, was selected to obtain drilling evidence for the freshwater aquifer revealed by the EM survey. Firstly, the sandy creekbed was delineated more precisely by an additional series of closely-spaced EM measurements along four cross-sections (see location map, Figure 57.1). The results are shown in Figure 57.6, which illustrates how well the sandy creekbeds can be traced by the EM method. The high lateral resolution becomes evident in the southern profiles, where only a very narrow strip separates the sandy creekbed from a second zone of high resistivities, which emerges on the eastern side. This latter zone is related to cover sands.

Along two of the cross-sections, a number of shallow exploratory boreholes were drilled, in which geophysical well logging was carried out, to measure both normal resistivity (Short Normal and Long Normal), and the natural gamma radiation. Water samples for chemical analyses were also taken. The boreholes are presented in Figure 57.7, in which the lithological columns and the resistivity logs have been drawn side by side. These logs correlate nicely with the EM resistivity anomalies, which are portrayed in the graphs above the cross-sections. The chloride contents, indicated opposite the well screens, confirm the presence of freshwater in the sandy creekbeds. The freshwater aquifers reach maximum thicknesses of approximately 15 m. The influence of aquifer thickness on the EM observations is evident from the borehole on the western edge of the creekbed in cross-section d-d', where the fresh/creekbed layer is thin, producing intermediate EM resistivities. Test drilling thus provided conclusive evidence that the observed EM anomalies do indeed correctly delineate freshwater-bearing aquifers.

THE GEO-ELECTRIC SURVEY

In order to acquire quantitative data on aquifer thickness and aquifer resistivity, a limited number of vertical electrical soundings (VES) were carried out at selected locations. During 1956 and 1959, a local

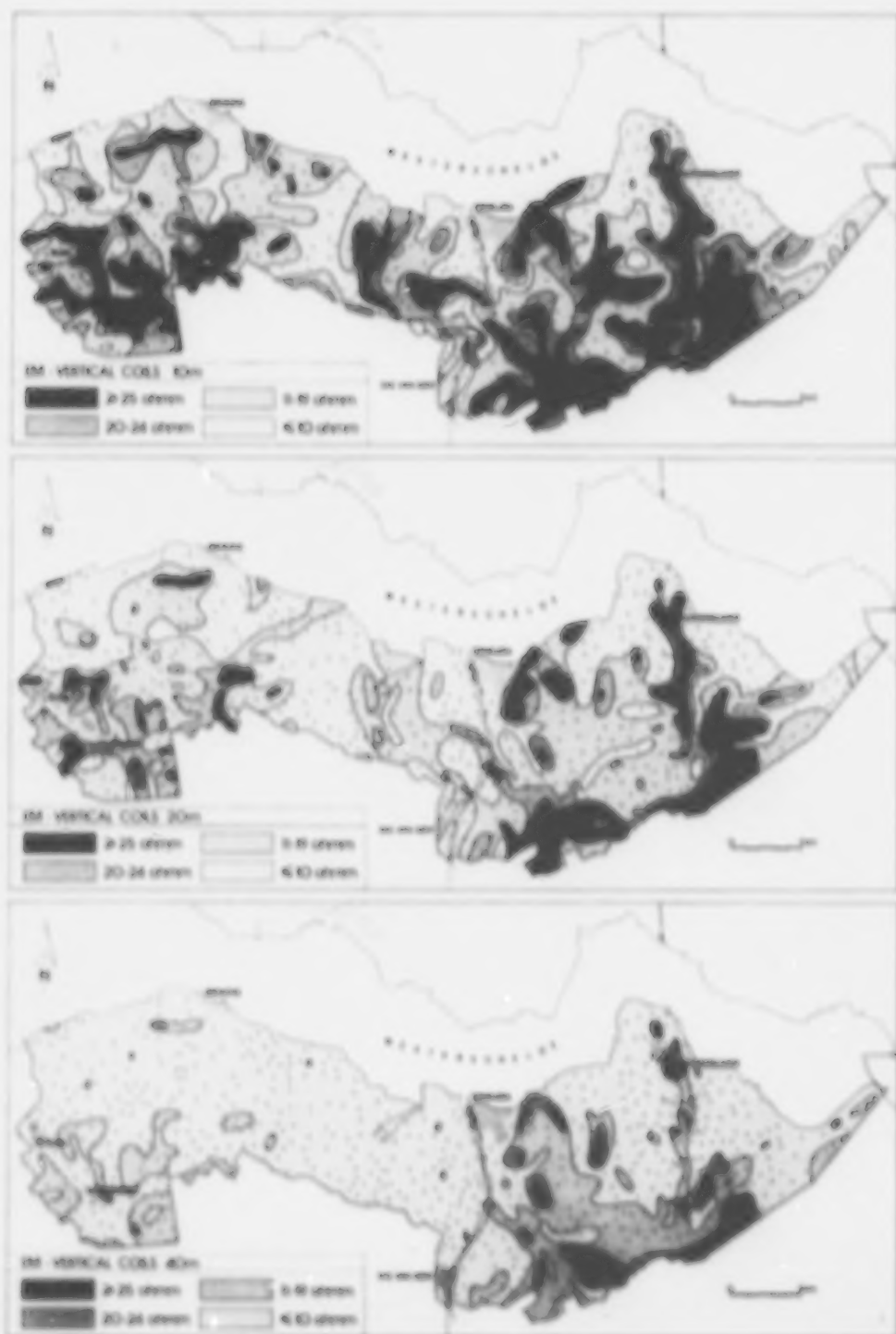


Figure 57.4. Apparent resistivity maps of the EM survey.



Figure 57.5. The relation between EM anomalies and shallow peat layers.

geo-electrical survey had been conducted (Van Dam and Van Rummelen 1960) near Terneuzen to investigate groundwater salinity in the surroundings of a creek that had been in open connection with the sea until 1952, when dikes were constructed to seal the entrance. All 21 soundings still revealed high salt concentrations in the shallow aquifer. Our EM survey, however, showed high resistivities in some parts of this area, and therefore a few new soundings were done at some of these former sites. This indeed confirmed that at present, thus after some 30 years, the aquifer has been partly desalinated.

The distribution of the geo-electrical soundings, including both old and new ones, is indicated on the location map (see Figure 57.1). Most of the 57 new soundings were, of course, located at sites where the EM survey indicated freshwater aquifers, but some VES were made in saline areas, as an additional check on the EM results. In Figure 57.8 two typical curves illustrate the large resistivity contrasts that arise from differences in water salinity. The two soundings are the most northerly ones made near a-a' and lie only 1 km apart (see Figure 57.1): one in the centre of a sandy creekbed, the other one outside it.

The VES curves not only provide information on the shallow aquifer but also on the deeper layers, as is illustrated by the examples in Figure 57.8. At the end of the curves, the apparent resistivities increase with depth. This is because the deeper clay layers have resistivities that, although low, are higher than the sands containing saline water. Owing to these contrasts, the vertical sequence of permeable sands and less permeable clays can be determined, leading to a more complete hydrogeological picture, as is illustrated by an east-west geo-electrical cross-

section through Zeeuw-Vlaanderen (Figure 57.9). Two important, thick, clay layers are distinguished, the lower one being of Eocene age and the upper one of Oligocene age. This latter clay layer is absent in the western part, probably as a result of tidal erosion, as is suggested by the abrupt end of the layer. Maps of the depth of the different layers show that these strata dip gently to the northeast. Sandy formations containing saline or brackish water are found below and between the clay layers. The brackish water originates from a freshwater flow of infiltrating rainwater in the neighbouring Belgian area.

Although these older sands and clays do not contain freshwater resources, knowledge of their vertical and lateral distribution is important, as it has direct consequences, both for modelling of the shallow freshwater aquifer and the EM survey. In the next section it will be shown that it does make a great difference for EM readings whether the "base" of the shallow freshwater aquifer is formed by a thick series of sands saturated with saline groundwater, or by a clay layer of low permeability.

The geo-electrical soundings taken at selected sites indicate that the shallow freshwater aquifer is rather uniform and continuous. The EM profile, drawn above the cross-section, depicts a more capricious pattern of peaks and troughs, reflecting the real, much more complex situation. The peaks and troughs of the EM anomaly agree well with the freshwater/saline water distribution as indicated by the geo-electrical cross-section, except in some parts in the centre of the profile, which is based on some of the old VES. The most outstanding EM peak coincides with an area where the shallow aquifer is formed by cover sands directly overlying Oligocene clays.

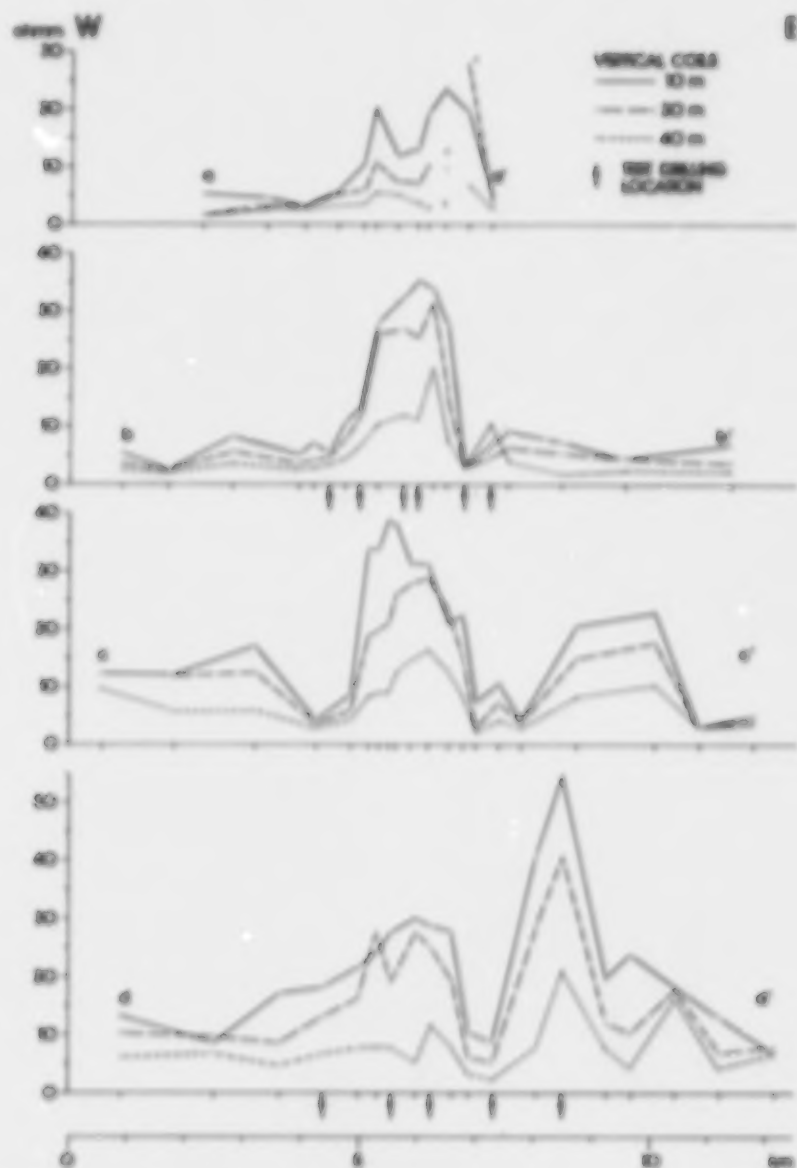


Figure 57.6. Detailed EM profiles over an infilled sandy creekbed (see location map, Figure 57.1).

The combined presentation of EM and VES data illustrates the advantages of the EM method for exploring limited, narrow, and irregular freshwater occurrences. The VES data, in contrast, furnish the quantitative data, showing that the freshwater aquifer has resistivities that vary from 30 to 70 ohm-m and reaches thicknesses of up to 25 m.

QUANTITATIVE ANALYSIS OF EM DATA

At first sight, the obvious way to link the apparent resistivities measured by EM to aquifer thickness

and salinity seems to be by model computations. For this purpose, the theoretical EM34-3 response (McNeill 1980a) for vertical coils was calculated for some simple two-layer models that are representative of the freshwater-bearing infilled sandy creekbeds in a saline environment (Figure 57.10). In model 1, the aquifer is 15 m thick and has a resistivity of 40 ohm-m; the latter corresponds approximately to medium-grained sands (formation factor F , which is the ratio between the formation resistivity and the water resistivity, is 4) saturated with water having a chloride concentration of

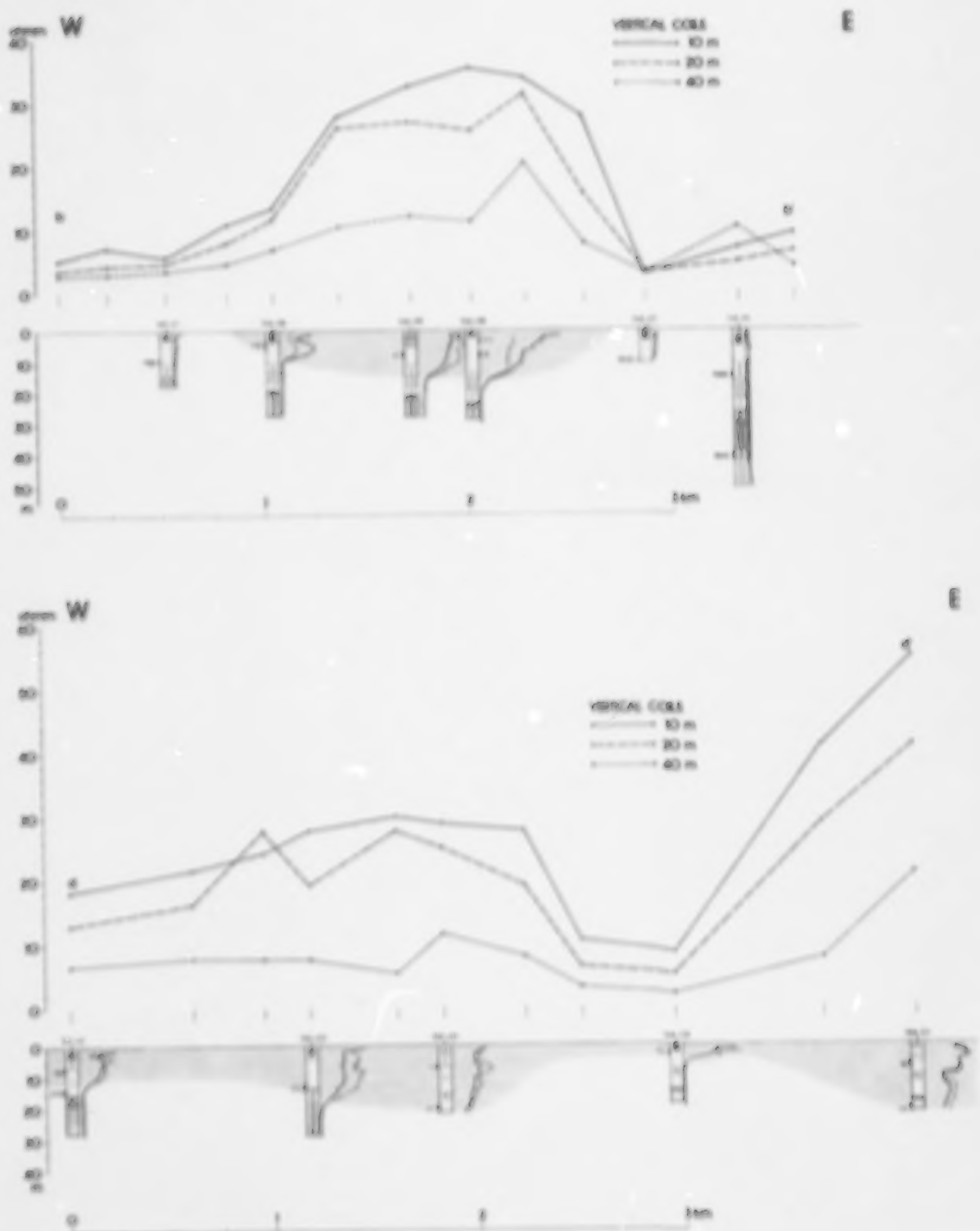


Figure 51.7. EM anomalies and resistivity logs in exploratory boreholes along two cross-sections of a sandy creekbed; shaded zones mark fresh and brackish water.

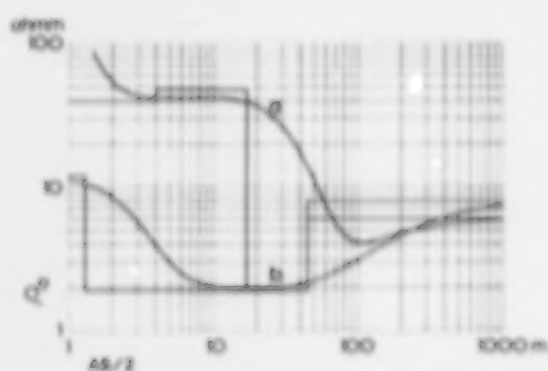


Figure 57.8. VES contrasts inside (a) and outside (b), a sandy creekbed near IJssel $\alpha-\alpha'$.

150 mg/L, a value that defines the freshwater/saline water boundary in the Netherlands. Below the aquifer the formation resistivity is 1.5 ohm-m, which agrees with very saline water of more than 10 000 mg/L Cl^- . The theoretical EM response to this model produces low values of apparent resistivity ($V-10 = 7.8$ ohm-m). This illustrates the large influence of the saline layer, even when the interface lies at a depth of 1.5 times the intercoil spacing. In model 2 the aquifer resistivity has been increased by a factor 2.5, giving 100 ohm-m, which corresponds to a much lower salinity of approximately 40 mg/L Cl^- . Yet the EM response hardly changes ($V-10 = 8.6$ ohm-m). Or in other words, the EM response is not sensitive to salinity variations in the sandy creekbeds. However, variations in thickness do influence the EM response. This is illustrated in model 3, where the thickness of the aquifer is twice that of model 1, leading to a considerable increase in EM values ($V-10 = 12.8$ ohm-m). Unfortunately, a similar effect is produced if the previous thickness is maintained, but the resistivity of the saline layer is slightly increased instead to a value of 2.8 ohm-m, which relates to a chloride content of some 5000 mg/L. Thus, the EM response is very sensitive to minor variations in the saline layer. This in fact is a general characteristic of the EM method, which prefers to look through a layer of high resistivity to one of low resistivity, rather than vice versa (McNeill 1980a). This property makes the method quite suitable for exploring for water in deserts, where the conductive target is covered by resistive dry layers. In Zeeuw-Vlaanderen, however, it is not the deeper layer one is interested in but the top layer, and it is precisely the effects of the shallow layers that is obscured by the deeper ones, as is illustrated by comparing models 1, 2, and 4.

The similar response over models 3 and 4 is a problem of equivalence, a well-known obstacle to the interpretation of VES curves. For EM34-3 data, equivalence is aggravated by the limited number of

observed points and the small depth interval. In fact, models 3 and 4 are only equivalent for the EM34-3 configuration. If more intercoil spacings had been recorded, then the equivalence problem in this two-layer case would have been resolved, especially if the intercoil spacings had been larger.

However, in the saline environment of Zeeuw-Vlaanderen an additional problem arises, caused by the instrumental constraints defined as "operating at low induction numbers". Similarly to the VES interpretation, the six observed EM values can be plotted in a logarithmic graph and be matched with theoretical curves, computed for both horizontal and vertical coil orientations (McNeill 1980b). Figure 57.11 shows a well log made in one of the exploratory boreholes. The true resistivity variation with depth, as indicated by the long normal (LN) graph has been schematized into five layers and further simplified into a two-layer model. Both models produce the same theoretical EM response at the available intercoil spacings. The theoretical curves for both coil orientations were computed for this two-layer model and were drawn in the logarithmic graph, accentuating the values at the intercoil spacings of 10, 20, and 40 m. However, the actual measured values at this site, also indicated in the graph, turned out to be much higher. This is a general feature in Zeeuw-Vlaanderen, where most of the values observed over sandy creekbeds are higher than 25 ohm-m, thus significantly higher than the theoretical values computed after the models in Figure 57.10. Therefore, it was concluded that the EM data of Zeeuw-Vlaanderen are not suitable for model interpretation.

It should be emphasized that it was never intended to apply interpretation by layer models to all 785 measurements, because this would negate the rapidity of the EM method, but rather to use a few characteristic models to define contour boundaries and to relate them to aquifer characteristics, such as salinity and thickness of the freshwater zones.

A different approach to analysing the EM data quantitatively is by seeking empirical relations between the observed values and aquifer characteristics. Such a correlation can only be attempted, of course, if these aquifer characteristics are known at a representative number of EM observation points. In Zeeuw-Vlaanderen this type of additional information is provided by water samples from boreholes, the geo-electrical soundings, and the geophysical well logs. In the correlation graphs of Figure 57.12, the observed EM values have been plotted against the data available on salinity and aquifer thickness. In all cases, the EM values are apparent resistivities determined with vertical coils spaced at 10 m. Empirical relations were established by a computer program for curve fitting using the least-square-error criterion.

In Figure 57.12(a), observed EM values have been plotted against chloride concentrations of water samples from boreholes. Only those samples that

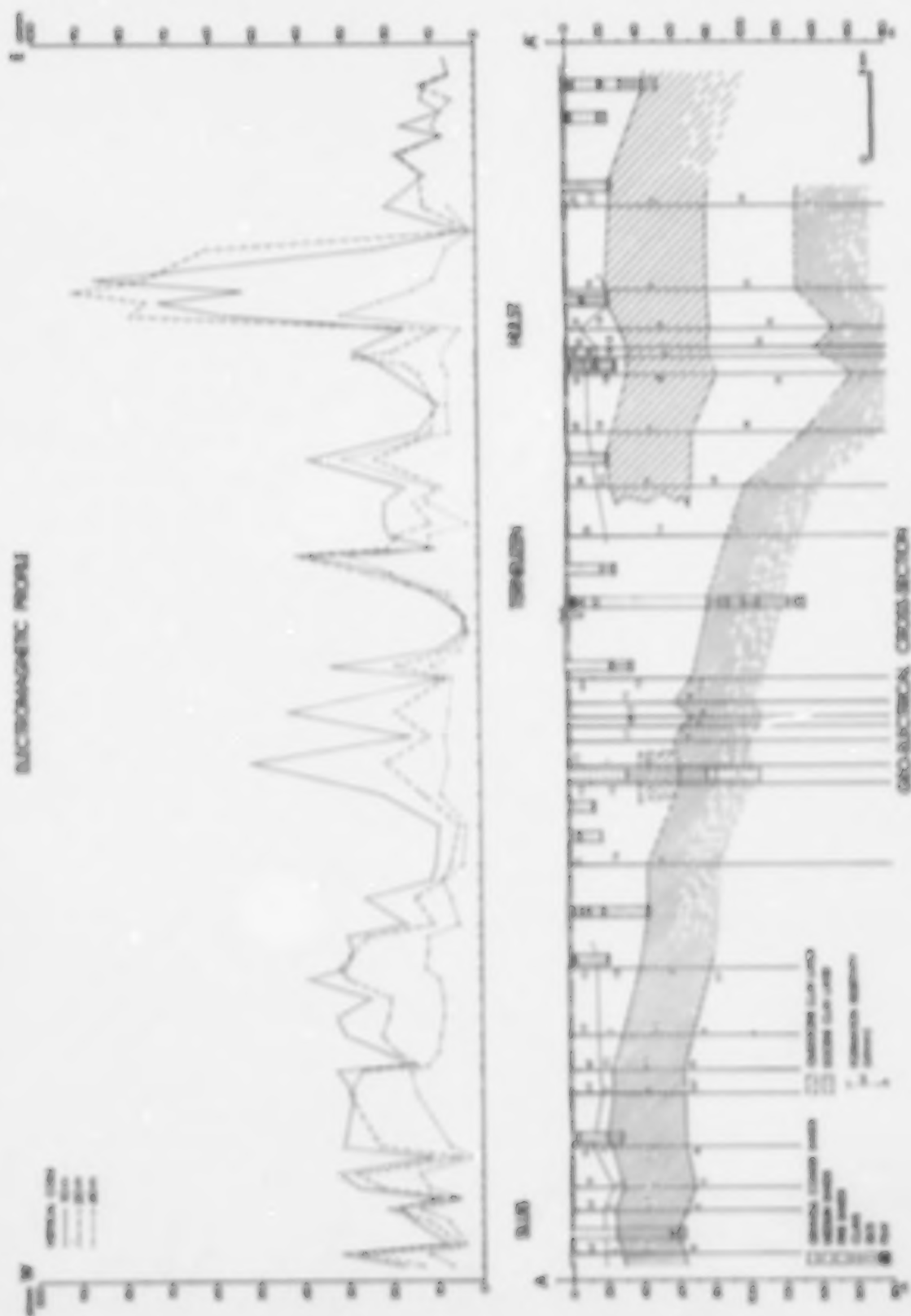


Figure 21.9. Geophysical cross-section A-A' through Zoster-Mandens, and channel EM anomalies.

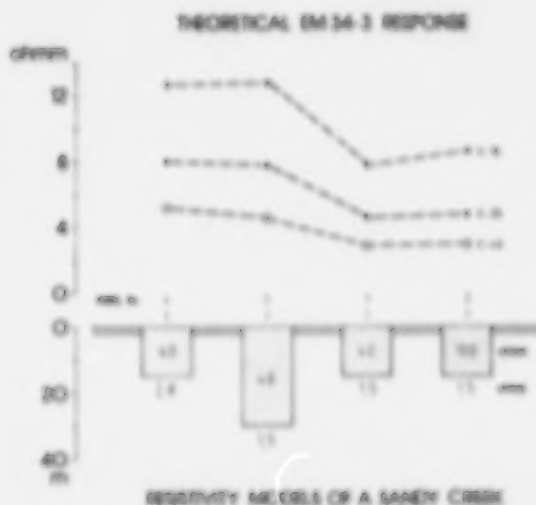
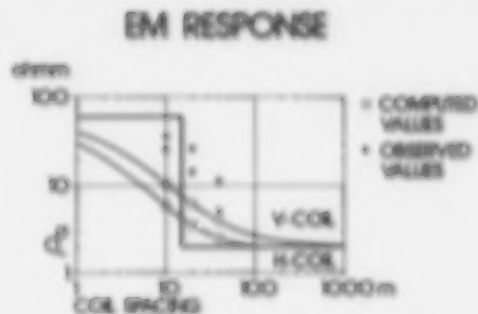


Figure 37.10. Theoretical EM response over four models of infilled sandy creekbeds.

were taken from screens at shallow depths (maximum 15 m) have been included. The result is a rather poor correlation, as witnessed by the scatter of the points and shown by the index of determination $R = 0.57$, which is a measure of how well a curve fits the data points with good fit corresponding to $R \approx 1$. One of the main causes of scatter is the variation in depth of the different screens. Consequently, in some boreholes the screens may tap water from above the freshwater/saline water interface, whereas in others they tap from below this interface. Thus, entirely different chloride concentrations might correlate with identical EM values. Other causes of the poor fit are the variations in aquifer thickness and in the resistivity of deeper layers, as explained above and illustrated in Figure 37.10. The correlation graph does show a general trend of decreasing resistivities with increasing salinity. All freshwater samples (less than 150 mg/L CF) coincide with EM values of 25 ohm-m or higher, and all EM values of less than 10 ohm-m relate to chloride concentrations of over 7000 mg/L. However, these relationships do not always hold.

Scatter caused by variations in screen depth can be eliminated if it is known that a water sample is representative of the freshwater aquifer. Here the importance of geophysical well logs becomes evident, because a resistivity log will ascertain whether a sample taken at a certain depth is from the freshwater aquifer or from different zones. Therefore, the water samples abstracted from the exploratory boreholes were compared with corresponding well logs, and 10 samples, found to be representative, were correlated with the observed EM values. This is illustrated in Figure 37.12(b), which shows a much better correlation and a determination index



WELL LOG 55A-218

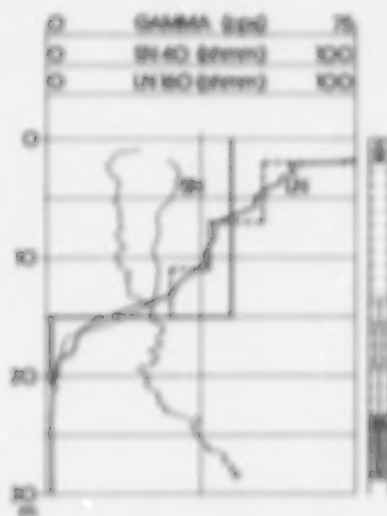


Figure 37.11. EM response, calculated from a resistivity model provided by a geophysical well log; observed EM values do not agree with the computed ones.

$R = 0.9$. The boundaries between fresh, brackish, and saline water correspond with 23.5 and 11.6 ohm-m. But in order to avoid an unjustified impression of great precision, these values were not used to define the boundaries of the contour maps (Figure 37.4). Instead, the rougher values of 25 and 10 were taken.

It must be emphasized that the good fit was obtained because of the large contrasts between samples from fresh, brackish, and saline water, which required logarithmic plots. If narrower ranges are taken, e.g. merely the saline zone, the correlation is much worse or even absent.

Thus far, the influence of aquifer thickness, which was shown to be large (Figure 37.10) has been ignored. To evaluate its effect empirically, the EM values observed at the test drilling sites were plotted against the thickness of the freshwater zone

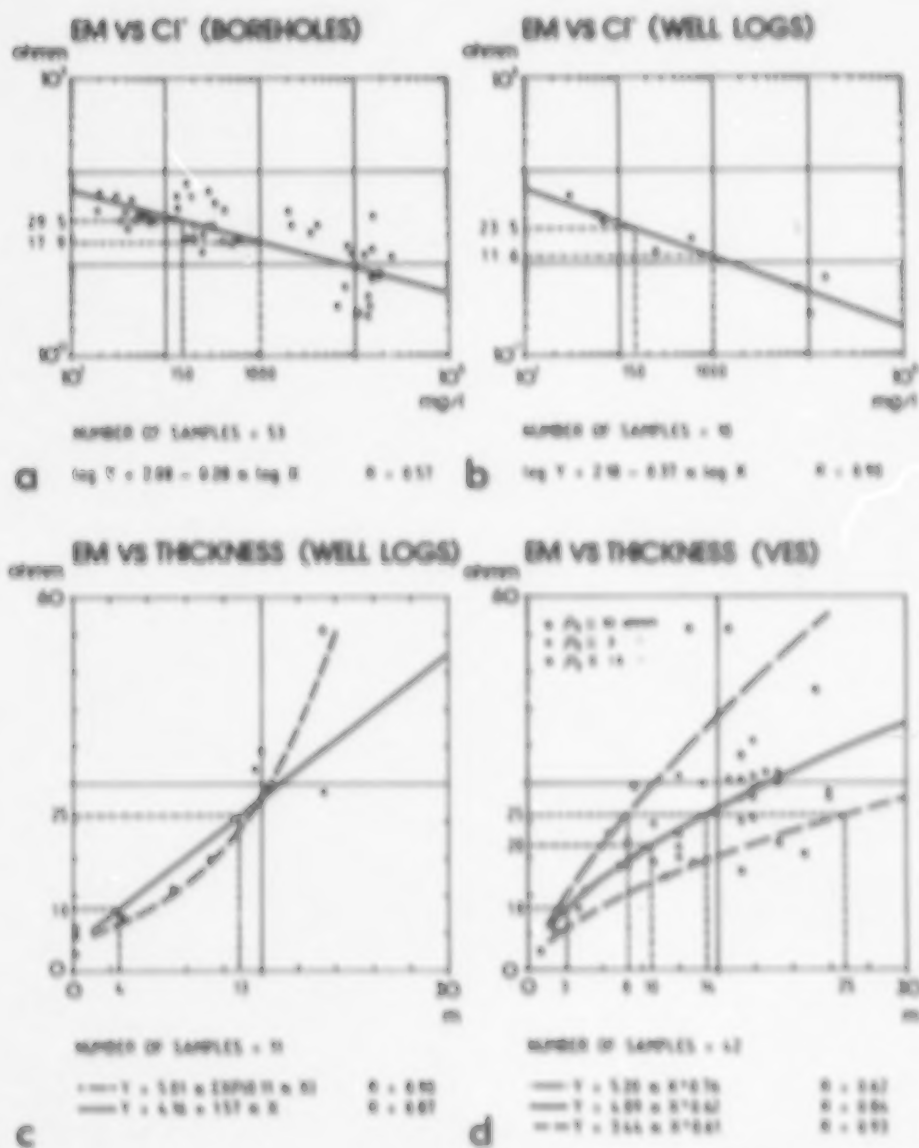


Figure 57.12. Correlation graphs relating observed EMH data (vertical coils spaced at 10 m) to aquifer characteristics.
(a) EM versus Cl^- in water samples from boreholes.
(b) EM versus Cl^- in water samples using well log data.
(c) EM versus thickness of freshwater zone determined from well logs.
(d) EM versus thickness of freshwater zone determined from VES.

as deduced from the geophysical well logs. This is shown in Figure 57.12(c) by the linear graph. The best-fitting curve is an exponential function. However, this result is distorted by effects other than variations in thickness. The exponential function is largely determined by the highest point, whose value is caused not only by the freshwater aquifer, but also by the underlying clay layer having a considerably higher resistivity than sands containing saline water.

If this point is left out, then the data fit best to a straight line.

The influence of the resistivity of the deeper layer is better demonstrated by Figure 57.12(d), where EM measurements observed at VES locations have been plotted against thicknesses deduced from geoelectrical soundings. Obviously, the correlation is poor if all points are included. The best fit, not

shown in the graph, is a power function with an index of determination $R = 0.75$. The cause of the large scatter becomes clear if the points are grouped on the basis of the resistivity of the deeper layer. A distinction was made between clays ($\rho_2 \approx 10$ ohm-m), saline ($\rho_2 \approx 2$ ohm-m), and extremely saline ($\rho_2 < 1.5$ ohm-m) conditions, and subsequently, the curves were fitted selectively. The three curves clearly illustrate the large influence exercised by the deeper-layer on observed EM values. An EM reading of 25 ohm-m may thus result from aquifer thicknesses of 8, 14, or 25 m, depending on the characteristics of the underlying layer.

It may be concluded that neither model computations nor empirical correlations lead to a precise, quantitative appraisal of the observed EM data. However, the latter approach permits a fair estimate to be made. In Zeewoer-Vlaanderen, values of 25 ohm-m or higher will, for the most part, indicate freshwater-bearing (Cl^- less than 150 mg/L) aquifers having thicknesses of more than 10 m, whereas values lower than 10 ohm-m will generally imply very saline water at less than 4 m below the surface.

The additional contour line of 20 ohm-m (Figure 37.4) was chosen to accentuate the gully structures on the maps, at the same time denoting zones that may still contain appreciable volumes of fresh water.

CONCLUSIONS

Geo-electrical soundings provide the most valuable geophysical information when investigating ground-water salinity problems. But if freshwater occurrences are scarce and restricted to small volumes, the electromagnetic method offers a more efficient approach. EM34-3 equipment enables a fast and detailed delineation of shallow freshwater aquifers in mainly saline coastal areas. The data obtained are not suitable for estimating water salinity or aquifer thickness precisely. To do this, VES measurements are still required, but their number may be greatly reduced on the basis of the results of the EM survey.

Curve matching or model computations for EM measurements are impossible or lead to erroneous results in saline areas. However, empirical relations between EM data and aquifer characteristics known from boreholes, well logs, and VES interpretation enable the optimal contour intervals to be selected for the maps of EM apparent resistivity and allow

some tentative estimates to be made of the characteristics of the fresh-water aquifers. Thus, in coastal areas like Zeewoer-Vlaanderen the best approach is to have EM tell us "where", whereas VES should resolve "what".

Finally, it should be pointed out that the electromagnetic method is an ideal tool for quickly and cheaply monitoring any changes in salinity that are likely to occur after water abstraction or artificial infiltration.

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58. Electrical Resistivity Survey for Groundwater Exploration in Basaltic Rocks of India

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ABSTRACT

The basalt of Western India, also known as the Deccan Trap, occupies an area of about 500 000 km² in Central and Western India. The Deccan Trap is a thick pile of basaltic lava flows which was not much disturbed after its consolidation in the Late Cretaceous to Eocene Period. The primary porosity of the Deccan Trap, caused by cooling cracks, fissures, and permeable flow junctions, is small. In the zone near the surface, secondary porosity is present due to weathering. Phreatic water occurs in weathered basalt and in laterite or local alluvial deposits overlying weathered basalt. Semi-confined water occurs in the fissures and flow junctions within the body of the hard rock. Both resistivity sounding and profiling are used for groundwater exploration in the Deccan Trap. The exploration is aimed at locating the zones of thick weathering, troughs in hard rock, zones of fracture concentration in hard rock, and old stream valleys. However, as the depth of investigation increases, the resistivity surveys become less accurate. A single fracture or a permeable flow junction a few millimetres-in-width, located at a depth of about 50 to 100 m is missed in the sounding curves. Also, on the lateritic plateau, the highly resistive crust at ground level obscures the underlying resistivity contrasts.

This paper deals with the scope and limitations of resistivity surveys for groundwater exploration in basaltic areas in India, and the evolution of appropriate technology in consideration of constraints on time and money, especially when the geophysical exploration is carried out for small farmers.

INTRODUCTION

Geophysical surveys for exploration of water in India are carried out on different technological levels, depending upon the status of the client and the consultant. When the surveys are carried out for Government Departments, Institutes, and Agencies by Government experts, sometimes in collaboration with foreign companies, the most modern technology is employed. Modern technology is also available for projects under aid programs sponsored by foreign agencies. Large industrial projects can afford to employ local or foreign consultants and use fairly high-level technology in site investigation. When the farmers, the small farmers having 2 to 5 ha of farmland, employ local consultants to explore water re-

sources in their tiny plots of land and pay consulting fees from their meager income, the technology has to be basic and cost effective. Using locally manufactured, low-cost resistivity meters, employing cheap unskilled labour, and keeping the technical staff in the Survey Team to a bare minimum, are some of the ways to keep the cost of the resistivity surveys within the reach of small farmers. The technology may be two or three decades old for geophysicists from developed countries, but it is still relevant to the needs of millions of small farmers in basaltic and other hard rock terrain in India.

Many times, there is only one technical person in the Survey Team who plays the roles of hydrogeologist, geophysicist, and adviser on well digging/drilling, water conveyance, and on utilization for maximum benefit through proper selection of cropping patterns. In order to select locations for resistivity soundings or alignments for profiling and to interpret the resistivity data correctly, the knowledge of local hydrogeological features is essential to the technical person. Collection of data from existing wells and bores in the Survey area is one of his primary duties before the geophysical work is started. Occurrence of groundwater in basaltic terrain has been briefly discussed below in order to acquaint the reader with the hydrogeological conditions under which a geophysicist has to work.

GROUNDWATER OCCURRENCE

Basalt, or the Deccan Trap, of the Late Cretaceous to Eocene age, covers about 500 000 km² in Central and Western India (Figure 18.1). The basaltic terrain extends from the Western coast mountains on to the Deccan Plateau which has a gentle slope eastwards. The elevation of the plateau ranges from about 1200 m in the west to about 300 m in the east. The annual rainfall, about 2000 mm in the coastal strip and 6000 mm in the western mountains is sharply reduced to about 300 mm in the central semi-arid part of the plateau. The precipitation occurs during the southwestern Monsoon season from June to September and is followed by a dry season consisting of four months of winter and four months of summer. Farmers get three cropping seasons per year, namely Monsoon, Winter, and Summer, each of about four months duration.

The Deccan Trap Formation is a pile of basaltic flows horizontally stacked one above the other. After consolidation, the pile was not subjected to appreciable disturbances. The primary porosity is due



Figure 18.1. Deccan Trap area in India.

to cooling cracks, fissures, fractures, joints, open junctions between two flows, and occasionally, a porous lava flow. Near the ground surface, the porosity is further accentuated by weathering processes. The overburden, that is the cover of weathered rock, caliche, alluvium or laterite, over hard basalt, usually contains the phreatic water body. In the fissures, fractures, and flow junctions within the underlying hard basalt, groundwater occurs under a semi-confined condition, and the circulation of water is mainly confined to depths of up to 100 m below ground surface.

The streams and rivers in the basaltic terrain are effluent, that is the dry season flow is maintained by the groundwater discharge from the catchment area. Only in the case of a pumping well located near a stream is it sometimes possible to induce seepage from the stream towards the well. Groundwater flow across surface water divides or ridges does not take place and each stream basin or subbasin can be treated as a separate hydrological unit. Annual recharge to the groundwater body is estimated to vary between 1 percent to 11 percent of the precipitation. The hard rock aquifer gets fully recharged by the end of Monsoon rains and during the remaining eight months of the year, this storage gets considerably depleted by pumpage and outflow. Groundwater flows from the margins of a subbasin towards the central valley, thereby causing drawdown of peripheral areas close to water divides. In many cases the phreatic water body in peripheral areas dries out by summer season. The average residence time for groundwater in a subbasin is five-to-six years.

Dug wells of about 5 m in diameter and about 6 to 15 m in depths are suitable for obtaining irrigation supply for small farms of about 2 ha in size. A dug well usually penetrates through the overburden

and goes a couple of metres into the hard basalt below. The water from the phreatic water body in the overburden passes into the well through the holes provided in the masonry retaining wall. Horizontal bores are often drilled radially outward from the well in order to increase the yield of water. The bottom part of the well serves as a storage space for water obtained from the overburden. Vertical bores of 100 to 150 mm in diameter are sometimes drilled through the bottom of dug wells (Figure 18.2). When these bores meet a permeable flow or junction, water under subartesian condition rises into the well. An average dug well supports up to 0.5 ha of crop in the summer season. However, yields as low as 1000 litres per day are considered useful. Recently, 150 mm diameter bores have been drilled to a depth of 100 m to provide a drinking water supply to many villages. The average yield of the bores is about 1000 litres per hour. In the event of failures of the hand pump fitted on a bore, the village women and children have to fetch drinking water from long distances, especially in the summer months. It is interesting to note that groundwater scarcity in the summer months is experienced in high rainfall areas as well as in low rainfall areas. In high rainfall areas, the thickness of the weathered zone is less, and surface runoff is greater due to rugged topography. In low rainfall areas, droughts are frequent and groundwater is in great demand because of the lack of a surface water source.

ELECTRICAL RESISTIVITY SURVEYS

Resistivity sounding and profiling have been very popular techniques for groundwater exploration for

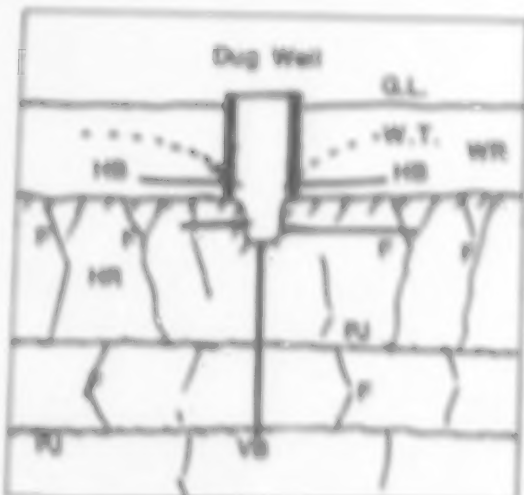


Figure 18.2. A dug-out-bored well. P: Porens and Pressure, MB: Masonry Boring, HR: Hard Rock, PJ: Permeable Junction, WR: Weathered Rock, W.T.: Water Table, VB: Vertical Bore, G.L.: Ground Level.

the past four decades. The maximum depth for a dug well is about 20 m. Profiling with the Wenner System ($\rho = 0$ to 30 m) is very useful for detecting: a) zones of pronounced weathering of hard rock, b) zones of fracture concentration in the hard rock, and c) old courses of streams in rejuvenated valleys. All of these are favourable locations for digging large diameter wells. Once these zones are delineated, it is customary to take a few soundings in them to determine the layering of the strata.

This is basically the technique for the exploration of shallow phreatic aquifers for locating suitable sites for dug wells. However, this method is also useful for siting deep bore wells of 150 mm diameter and 50 to 100 m depth. Although the bore wells derive their supply from the semi-confined groundwater within the hard rock, the deeper network is hydraulically connected to the phreatic water. In many cases therefore, high yield bore wells occur in the zones of plentiful phreatic water.

As the depth of exploration increases, the resistivity interpretation becomes more qualitative in nature. Water bearing joints and permeable junctions of small dimensions do not show on the sounding curve. Even a thick (1 to 2 m) horizontal, porous and permeable lava flow does not appear in the sounding curves taken at stations in valley regions, due to the low resistance of the overlying soil and weathered rock. If such a flow continues from the valley to the water divide, where the surface strata are resistive, a sounding curve at a station near the water divide often indicates the flow.

Recharge from rainfall over a watershed or a basin gradually seeps towards the central stream in the basin, as stated earlier. But all the bores or wells on the stream banks are not successful. Resistivity profiling along the stream banks is used to locate the pockets of better weathering for locating new well sites. Sometimes, radial measurements around a central point in a flat terrain can be used to locate the direction of fracture orientation in hard rock.

Interpretation of the resistivity sounding data is done by curve matching. The resistivity of hard, massive basalt is above 100 ohm-m. Water-bearing weathered or fractured strata have resistivities between 10 to 15 ohm-m. Irrigated soil has values between 1 to 20 ohm-m. Saline water zones give values less than 5 ohm-m. On laterite plateaus, phreatic water occurs at the junction of the laterite with underlying basalt within about 30 m of the surface. But exploration by the resistivity method may sometimes become difficult if the ground surface is covered by a hard encrustation, having a resistivity

of more than 1000 ohm-m. Exploration is relatively easy in valleys covered with laterite soil.

INSTRUMENTATION AND COST

Instruments used in the survey are indigenously manufactured and can be repaired without delay when necessary. Resistivity meters, using low frequency A.C. input to the ground, cost around US \$1000. D.C. meters are much cheaper. Recently, resistivity meters with digital readout and signal averaging facilities are also being manufactured in India. But their prices are around US \$2000.

The cost of a resistivity survey for well siting and allied consultation to the farmer should not exceed about 5 percent of the cost of the well. A dug well of 8 m diameter and 12 m depth with horizontal and vertical bores in the bottom would cost about US \$3000. A trial pit or a few trial bores of 20 to 30 m depth, however, can be completed within US \$800 to US \$1000. For a deep bore of 150 mm diameter and of 100 m depth, drilled with DTH pneumatic rig, the cost would be around US \$1000. The farmer would therefore, happily pay around US \$10 for a groundwater survey on his farm up to 5 ha in area, and for consultation on the location, depth, and diameter of his proposed well. The geophysical survey has to be planned in consideration of this US \$50 barrier for technical fees payable by the small farmer.

CONCLUSION

1. Basalts, or the Deccan Trap, in Western and Central India are poor aquifers compared to the basalts of Snake River Valley, U.S.A., Hawaii, or Israel. However, whatever small supply is available from them is extremely important to millions of small farmers for the irrigation of their tiny farmlands.
2. Resistivity sounding and profiling are useful tools for the exploration of zones having a rich phreatic aquifer in weathered rock, caliche, alluvium, and laterite overlying the hard basalt. These techniques have a limited use in the exploration of deeper semi-confined water in the network of unconnected joints, fissures, flow junctions, and so on within the hard rock. However, the fact that at many places such a network is more accumulated under the zones of rich phreatic aquifers makes them indirectly useful for deeper exploration also.
3. For rendering technical services to the small farmers, the exploration and consultation fee has to be kept low, within the US \$50 barrier.

59. Hydrogeological Interest of Aeromagnetic Maps in Crystalline and Metamorphic Areas

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ABSTRACT

Much of the world has been covered systematically by aeromagnetic surveys, principally for use in geological mapping and mineral prospecting. In Africa about one half of the continent has been surveyed and in areas of crystalline or metamorphic rocks, the coverage is probably better than 75 percent.

Studies by the authors have found that much of the information derived from these surveys has direct hydrogeological interest. Lithologies revealed by the magnetic textures often correlate with variations in supracrustal development. Most importantly, interpreted faults and dikes are found to represent zones of increased groundwater yield.

Aeromagnetic surveys carried out in Burkina Faso in the period 1970 to 1977 were used by the principal author in an evaluation of existing geophysical surveys for locating new water wells.

A systematic comparison of data furnished by geological mapping, photogeology, and LANDSAT imagery with results provided by the aeromagnetic survey is conclusive. The aeromagnetic data provided information from deeper in the ground and showed numerous and extensive faults and dikes that are not reflected in the present land surface and are therefore not detectable by the other methods.

The results of 182 wells and boreholes clearly show that the groundwater yield, less than 600 m from an interpreted fault is much higher than that from more distant points. In fact, the yield seems to be inversely related to distance from an interpreted fault or dike, up to a distance of 3 km. The tectonic origin of these features is thereby confirmed and their hydrogeological interest established.

INTRODUCTION

A wealth of airborne geophysical data, mainly aeromagnetic, exists worldwide, and is generally available (sometimes interpreted and sometimes not) to the exploration community.

In this paper we illustrate, with examples from Africa and India, how geological information pertinent to groundwater exploration is obtained from aeromagnetic survey data.

Specifically, we show that, in a crystalline basement area of western Africa, there is a direct correlation

between the yield of boreholes and wells and their proximity to faults and dikes determined from aeromagnetic data.

AEROMAGNETIC SURVEYS

The airborne magnetometer has been used extensively since the late 1940s for geological mapping as well as direct and indirect mineral and petroleum prospecting. Often the magnetic method is applied in conjunction with other sensors such as electromagnetic and gamma-ray spectrometers. The approximate level of activity, broken down by method and application, is given in Figure 59.1. To date, very little airborne geophysical surveying has been done for purely hydrogeological applications.

The popularity of the aeromagnetic method stems from a number of factors:

1. It is relatively inexpensive by comparison with conventional geological mapping and ground geophysical surveys.
2. The method is unaffected by the presence of non-magnetic surface materials such as a cover of soil or water.
3. Large and inaccessible areas can be covered rapidly. Typical programs may take from a few months to one or two years from start to finish.

For these reasons, and others, the aeromagnetic method has been very widely applied, and some countries have virtually 100 percent coverage.

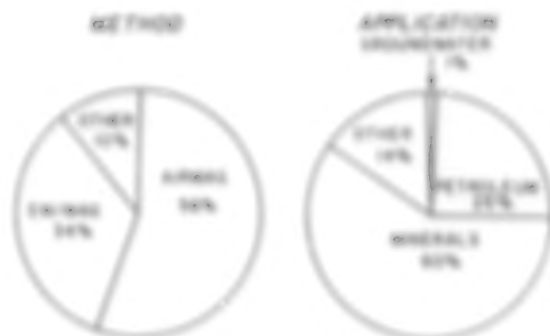


Figure 59.1. 1980 worldwide activity in airborne geophysics. Total reported expenditures: \$18 million (after *The Leading Edge*, Volume 6, Number 8, 1987).



Figure 18.2. Estimated aeromagnetic coverage of Africa.



Figure 18.3. Basement areas of Africa.

Among these are the African countries: Ivory Coast, Botswana, Algeria, Nigeria, Tanzania, Zambia, and Malawi. Average coverage in Africa and Asia is probably in the order of 10 to 40 percent. Areas of crystalline basement have the most dense coverage, probably exceeding 75 percent worldwide.

Figure 18.2 shows the estimated aeromagnetic coverage of Africa and Figure 18.3 outlines the areas of igneous and metamorphic rocks. Most of

these data can be obtained without difficulty from the Geological Survey departments of the governments concerned.

HYDROGEOLOGICAL APPLICATIONS

Groundwater in crystalline basement areas is controlled primarily by two factors: tectonic fracturing, and surface weathering. Figures 18.4 and 18.5 illustrate the influence of these two factors on water dis-

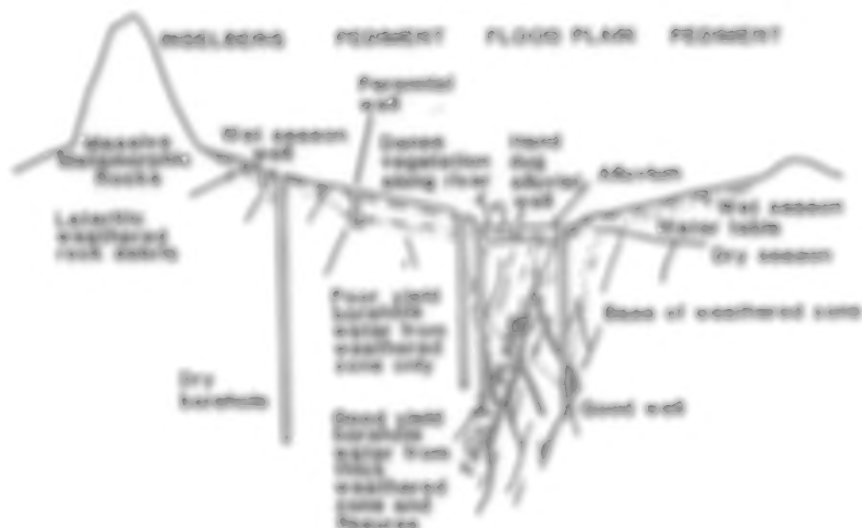


Figure 18.4. Diagrammatic basement complex hydrogeology (after Clarke 1965).

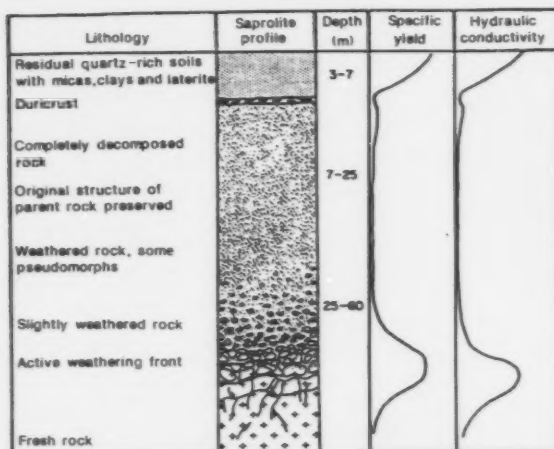


Figure 59.5. A typical saprolite profile over the crystalline Basement Complex in central Africa. The variations in specific yield range from 10^{-1} to 10^{-5} , while the hydraulic conductivities are in the order of 10^{-2} to 10 m/day (after Jones 1985).

tribution. It is evident that a method that will lead to the most heavily faulted areas and/or those of deep-

est saprolite development should be of considerable value in groundwater exploration.

Faults are commonly displayed indirectly in airborne magnetic surveys. They can manifest themselves as:

1. sharp gradients forming a linear boundary between areas of different magnetic level, relief, or texture. These may be fault contacts and are sometimes difficult to distinguish from unfaulted, linear contacts.
2. disruptions and/or deflections of magnetic trends. These are commonly wrench faults or shears, often with distinguishable lateral movement. They are the easiest types of fault to recognize though they have no direct magnetic expression.
3. linear magnetic lows within country rocks of moderate or high magnetic relief. These are usually zones where surface weathering or hydrothermal alteration has oxidized magnetite to hematite or limonite.
4. narrow, linear features with direct magnetic expression. The magnetic response in these features may be due to secondary magnetite resulting from metamorphism or to narrow dikes intruded in pre-existing faults.

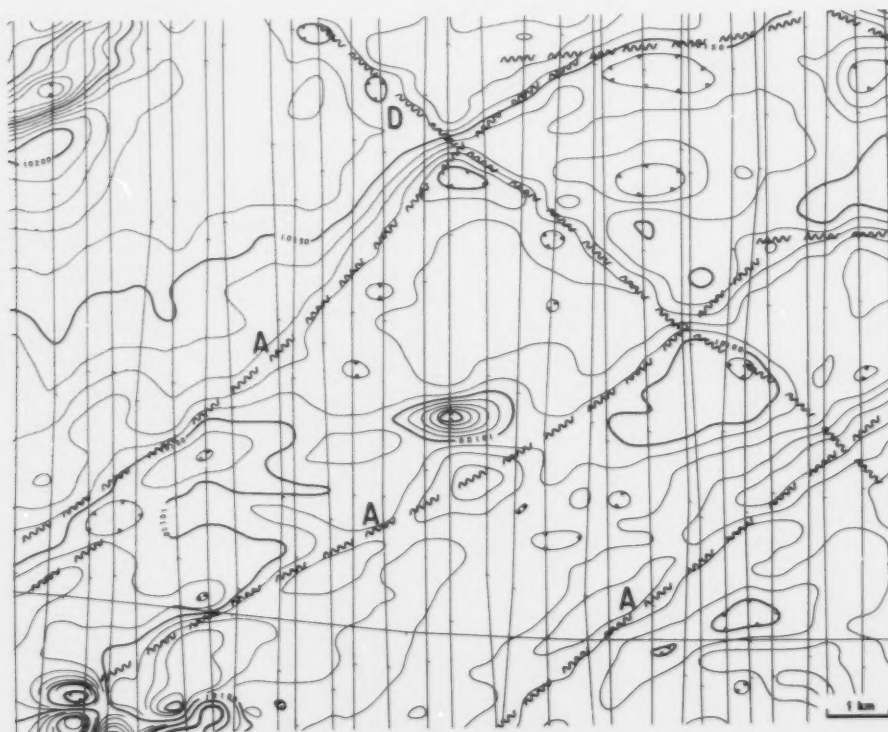


Figure 59.6. Aeromagnetic expression of fault-contacts (A) in metavolcanics and igneous intrusive rocks (Burkina Faso); cut by dike-filled cross fault (D).

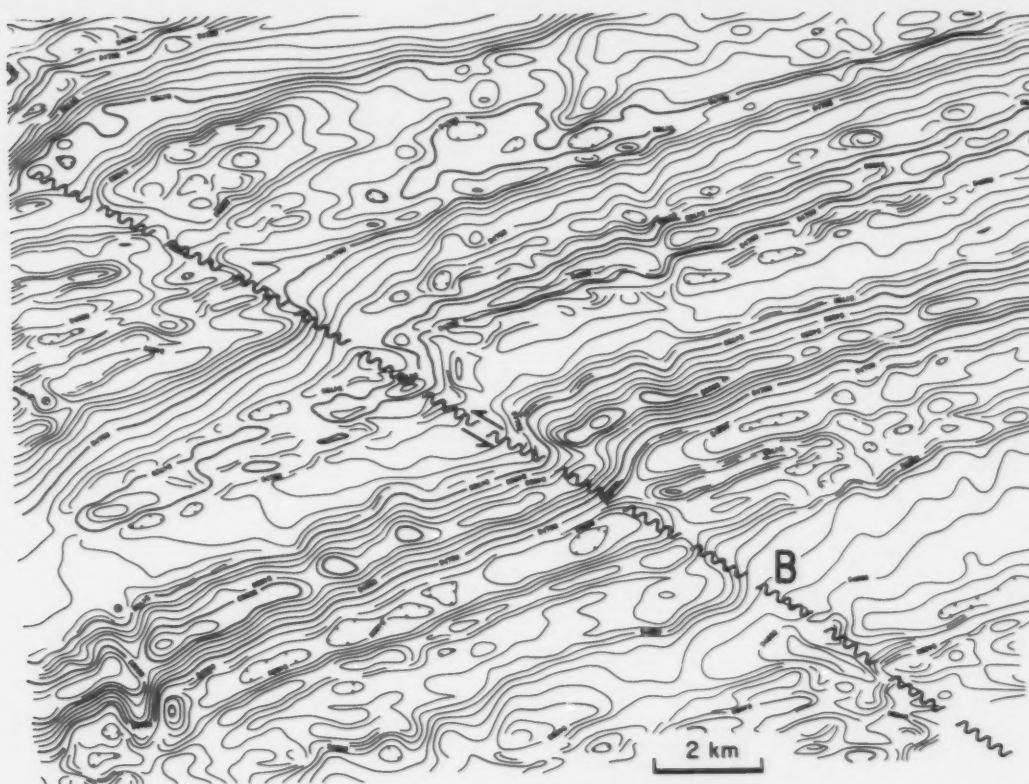


Figure 59.7. Aeromagnetic expression of a wrench fault with left-lateral movement in metasedimentary rocks (eastern Canada).

Figures 59.6 to 59.9 show illustrations of these four styles of "aeromagnetic faults".

With respect to saprolite development the most important information that can be provided by aeromagnetics is pseudo-lithology. The percent magnetite in the rock together with its spatial distribution are used routinely to characterize magnetic facies into pseudo-lithological units. Typical of these are such categorizations as: mafic versus intermediate-felsic volcanosediments; mafic-ultramafic versus intermediate-felsic intrusions; and various categorizations of volcanics and sediments based on metamorphic grade. The supergene weathering of these rocks follows a pattern governed partly by lithology and partly by structure. Areas of thick saprolite development may be represented by the less quartz-rich facies and zones of jointing or well-developed schistosity (Goldrich 1938).

The combination of major faulting and a thick

saprolite might be supposed to represent a favourable target for groundwater exploration.

In order to test this hypothesis a study was commissioned by F.A.O. and carried out by the senior author in 1981 (Astier 1981). The area selected was northeastern Burkina Faso where, in the period 1972 to 1977, regional aeromagnetic surveys were conducted under a C.I.D.A. program (Survair *et al.* 1977). The purpose of the study was to examine, in an area of 25 000 km², including a wide variety of basement lithologies, the correlation between aeromagnetic faults and the yield of existing wells and boreholes. The results of the study are reported on later in this paper.

Ground geophysical studies have since been conducted in the area by various organizations for the purpose of siting boreholes. Early results appear to confirm that structures determined aeromagnetically can indeed be located on the ground and that higher than average groundwater yields are obtained in their vicinity.

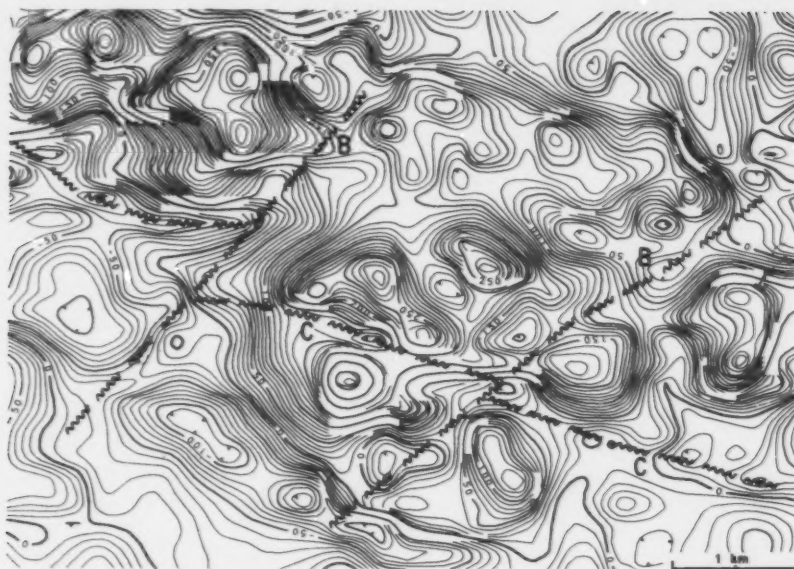


Figure 59.8. Aeromagnetic expression of a hydrothermally altered fault zone (C) in basic volcanic and igneous rocks (northwestern U.S.A.); cut by cross faults (B). Magnetic low is caused by depletion of magnetite through oxidation.

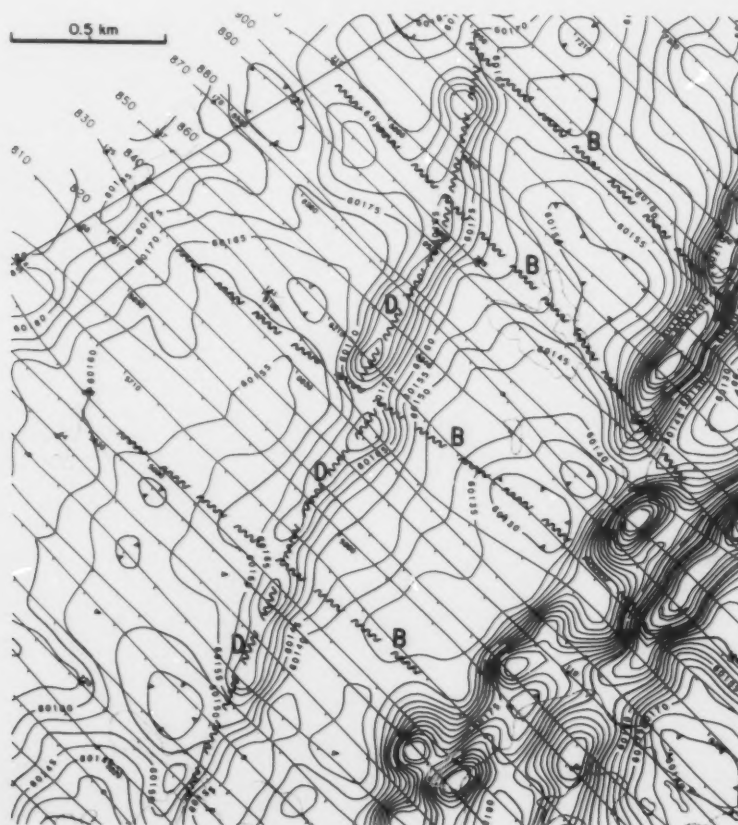


Figure 59.9. Aeromagnetic expression of a hydrothermally altered fault zone (D) in metamorphosed volcano-sedimentary rocks (northern Canada), cut by wrench faults (B).

AEROMAGNETIC INTERPRETATION, BURKINA FASO

Following the aeromagnetic surveys shown in Figure 59.10 which covered approximately 200 000 km² at a line interval of 500 m, interpretations were carried out by Terra Surveys Limited, Ottawa (blocks D and E) and Paterson, Grant and Watson Limited, Toronto (blocks A to C). The second author was responsible for the interpretation of blocks A, B, and C, and for integrating the two interpretations over the whole survey area (Paterson, Grant and Watson Limited 1985).

In order to understand the kind of structural information that can be obtained from such a survey and to appreciate its limitations, some brief illustrations of the results are presented. Plate 59.1 (see Colour Folio near back of book) shows the total magnetic field of the entire survey area as a colour image wherein the magnetic highs are represented by the red end of the colour spectrum and the lows by the blue end. It should be noted that, because of proximity to the magnetic equator, areas of strongest magnetization (including most of the Birrimian mobile belts) are represented by magnetic lows. At the scale of this particular illustration only the most regional structures are visible, but it is possible to observe northeast-trending faults of major dimensions as well as swarms of northwesterly trending narrow magnetic anomalies representing a second family of faults, generally occupied by dolerite dikes.

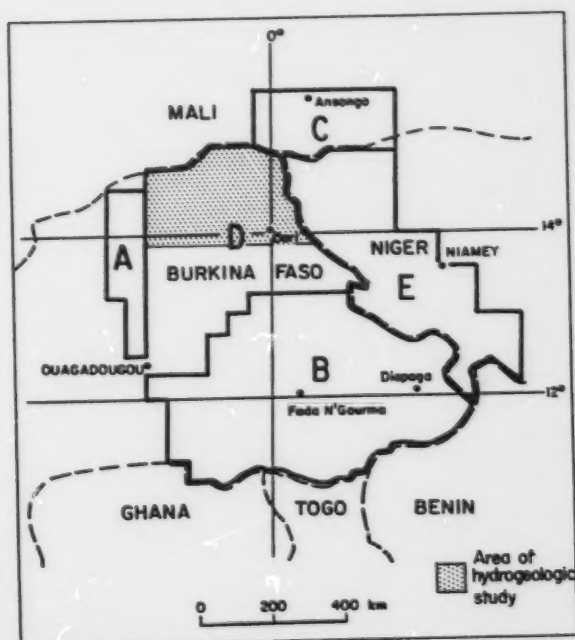


Figure 59.10. Aeromagnetic Surveys, Liptako-Gourma, western Africa.

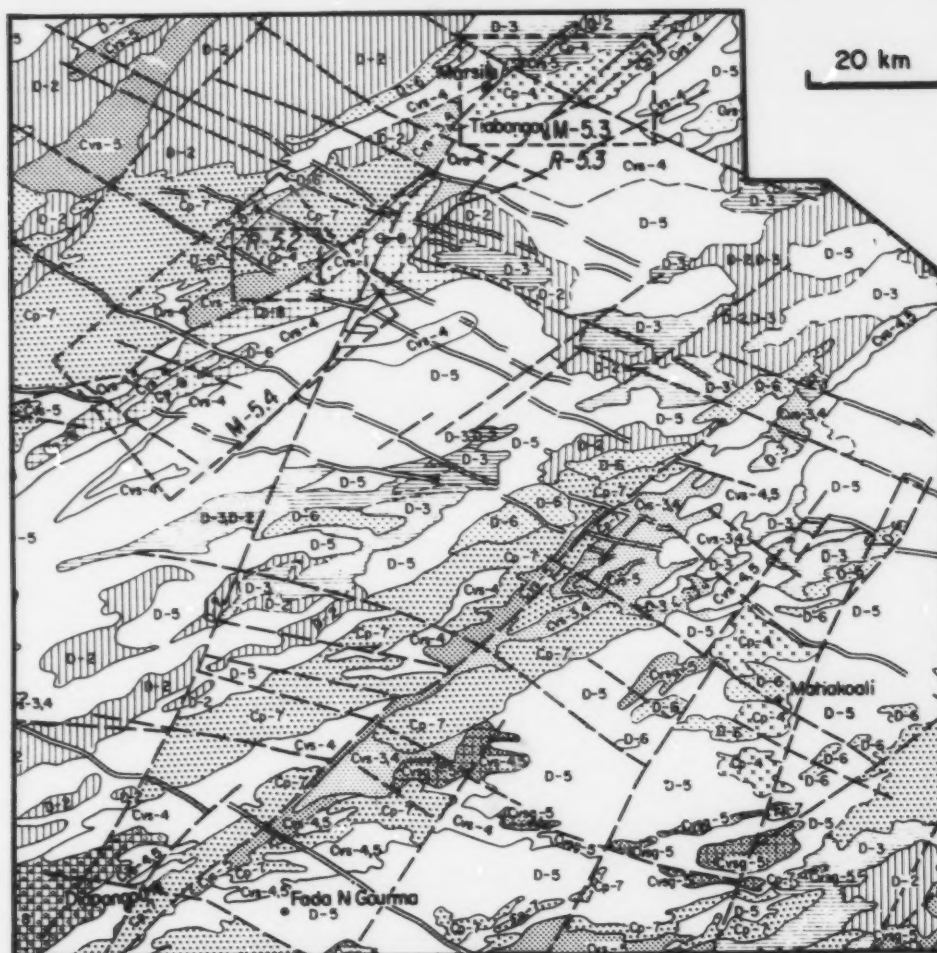
Interpretation of the data was carried out mainly at the 1:200 000 scale in sheets of approximate dimensions 65 cm by 65 cm. One such sheet is the Fada N'Gourma sheet, illustrated again as a colour image in Plate 59.2 (see Colour Folio near back of book). A simplified geological interpretation of this sheet is given in Figure 59.11. At this scale it has been possible to delineate the two major fault systems with some accuracy. Relative movement can often be identified at the junctions of the faults and where the faults offset stratigraphic and intrusive units. The northwest-trending system, with its associated dolerite dikes, is most noticeable. Some of the dikes are continuous for hundreds of kilometres. The faults are more continuous still and are interpreted to predate the dikes.

Additional interpretation was done at the 1:100 000 scale in areas of particular interest. Figure 59.12 shows the magnetic contours in one such area with the detailed geological interpretation superimposed. At this scale still further resolution is obtained of both structure and lithology, leading to greater potential precision in the selection of targets for groundwater exploration. As part of the ground truth studies accompanying the aeromagnetic interpretation several ground magnetometer and gamma-ray spectrometer traverses were conducted in the area. Figure 59.13 shows the results of a traverse over the interpreted Fada N'Gourma Fault. The position of the fault was confirmed and the greater resolution of the ground data verified the fault as a contact between Birrimian basic volcanics and granite.

COMPARISON WITH GEOLOGICAL MAPPING AND LANDSAT INTERPRETATION

As part of the hydrogeological study the aeromagnetic interpretation in part of Block D (see Figure 59.10) was compared with mapped geology (Delfour *et al.* 1970), a geological photointerpretation (Comité Interafricain d'Etudes Hydrauliques, C.I.E.H. et Géohydraulique 1981), and a LANDSAT interpretation (Travaglia 1979). Figure 59.14 shows a comparison between the aeromagnetic interpretation and the mapped geology in the vicinity of Markoy in the extreme north. It is noted that the geologically mapped faults and dikes are much fewer than those interpreted from the aeromagnetics. The regional Markoy Fault is recognized by both methods, as are some of the northwesterly trending dikes. However, the magnetic data have delineated the features with much greater continuity, owing of course to the ability to trace the magnetic features under the prevailing cover of residual soil and transported sand.

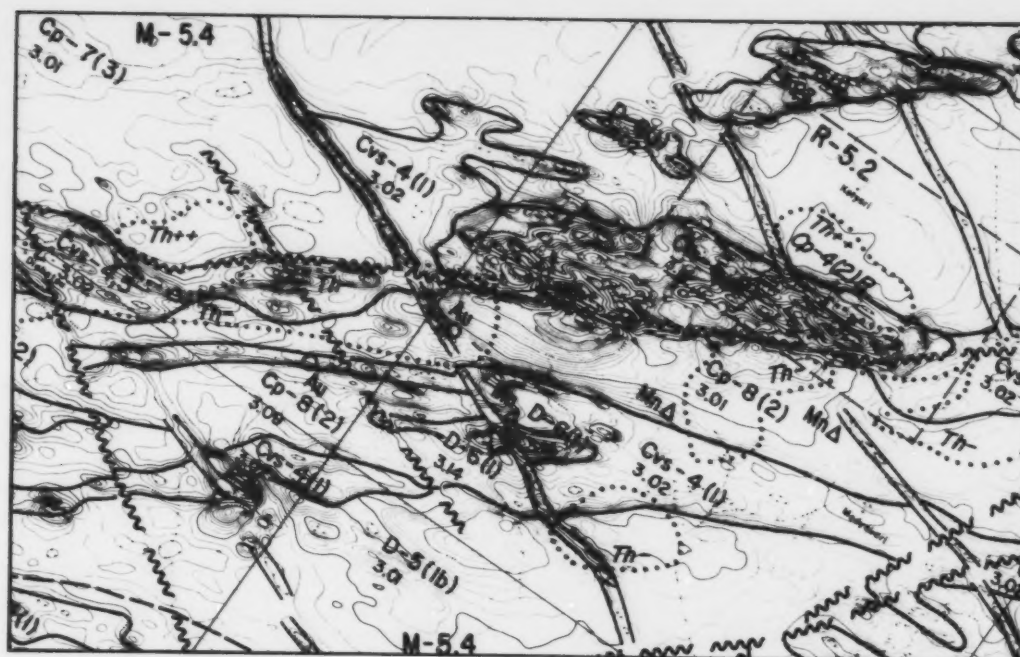
In the Gorom Gorom-Dori area, further south, a comparison was made of faults determined from LANDSAT, geological mapping/photogeology, and



LEGENDE GEOPHYSIQUE

- Contact géologique interprété
- - - - - Contact géologique gradationnel ou enfoncé
- - - - - Faille interprétée
- Dyke de dolérite interprété
- Cp-2 Faciès magnétique (2) de la formation géologique Cp-2
- Cp-6 Association géologique probable d'une unité radioactive
- Aor-1/D-5 Couverture non-magnétique Aor-1 au-dessus de la formation interprétée D-5 (1b)
- M-3.3 Région détaillée M-3.3

Figure 59.11. Simplified geological interpretation of the Fada N'Gourma aeromagnetic map (Plate 59.2); showing detail area M-5.4.



LEGENDE GEOPHYSIQUE

— — — — —	Contact géologique interprété
— · — · — · —	Contact géologique gradationnel ou généralisé
— · — · — · —	Contact géologique enfoncé
— — — — —	Contact entre deux faciès magnétiques d'une formation géologique
.....Th+.....	Contact entre deux faciès radioactifs, le Th s'accroît au côté indiqué
— — — — —	Limite de la couverture des roches indiquées
~~~~~	Faïte interprétée et direction du mouvement latéral / vertical
— — — — —	Dyke de dolérite interprété
Sgi (M)	Faciès magnétique (M) de la formation géologique Sgi
9.17	Unité magnétique correspondante
Ct (R)	Association géologique probable d'une unité radioactive
Sgi / Byl	Couverture non-magnétique Sgi au-dessus de la formation interprétée Byl
— — — — —	Kimberlite interprété probable

Figure 59.12. Aeromagnetic contour map and simplified geological interpretation of detail area M-5.4 (part of Fada N'Gourma Sheet, Plate 59.2, Figure 59.11).

the aeromagnetic interpretation. It can be observed (Figure 59.15) that there is rather poor correlation between the three sets of data. The aeromagnetic faults have greater continuity and appear to agree not too badly with the geological faults at specific locations. The LANDSAT imagery faults, with few exceptions, have little correlation with either of the other data sets.

It was concluded that, because of the extensive soil cover and lateritic development in the area, bed-rock features such as faults and contacts are very difficult to recognize in LANDSAT imagery or conventional aerial photography. Furthermore, most

faults in these heavily weathered crystalline basement terrains have little or no present surface expression. Where outcrop is available, however, geological mapping generally confirms the presence of the aeromagnetically interpreted features.

## HYDROGEOLOGICAL STUDY, BURKINA FASO

The area chosen for the hydrogeological study comprises 25 000 km² lying north of Latitude 13°45' (see Figure 59.10). The area was considered large enough to provide significant results and it contained

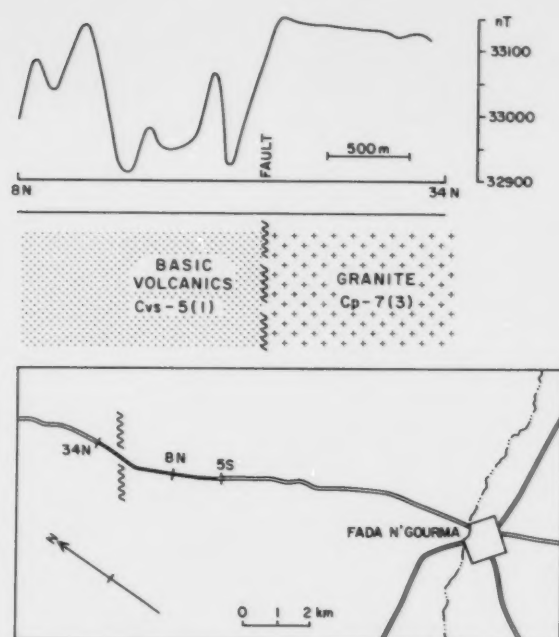


Figure 59.13. Ground magnetic traverse T-6-1 Burkina Faso.

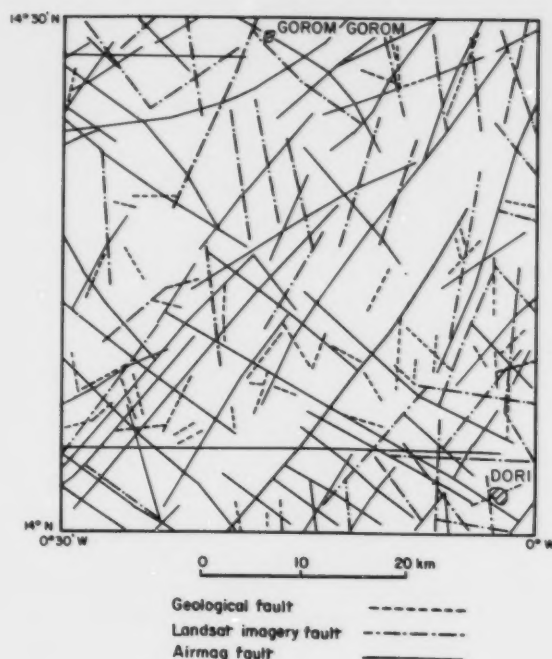


Figure 59.15. Comparison of airmag faults with LANDSAT imagery and geology in the Dori-Gorom Gorom area.

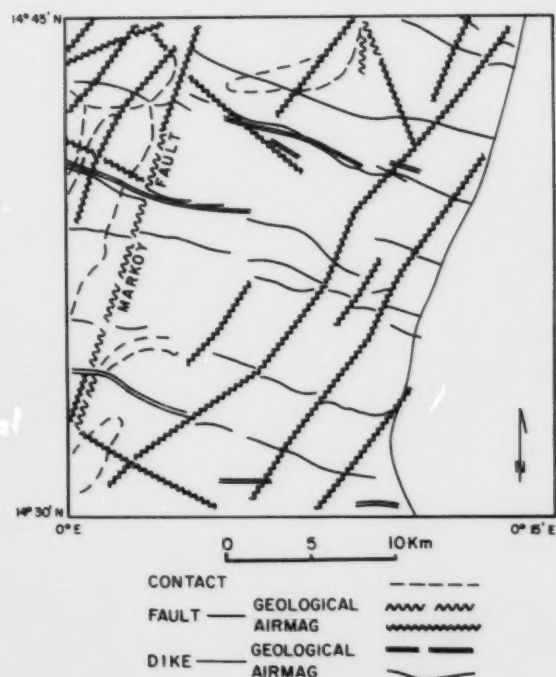


Figure 59.14. Comparison of aeromagnetic interpretation with geology.

all the typical Precambrian formations including: syntectonic granites covering large stretches of land; posttectonic granites in small massifs; migmatites; dolerite and gabbro intrusions, and andesites, amphibolites, schists and quartzites of the Birrimian volcano-sedimentary sequence.

The number of wells and boreholes examined was 258. Information regarding 212 of them came from an inventory prepared by the Direction de l'Hydraulique et de l'Equipeement Rural (H.E.R.) (1979). The other 46 boreholes are part of a Bureau de Recherches Géologiques et Minières (B.R.G.M.) report (Sourisseau 1980).

The water production data is not consistently reliable. The boreholes drilled under BRGM supervision are accurate because the specific yield and transmissivity were calculated from pumping tests. The H.E.R. inventory, on the other hand, classes well production as poor, mean, or fair though the borehole yield is quantified.

Of the 258 wells and boreholes, 182 (15 wells and 167 boreholes) were retained for the study, a number high enough to allow errors concerning production to compensate one another. The remaining 76 wells and boreholes were rejected either because of doubtful location or production, or because it was apparent that the depth reached did not adequately sample the structure responsible for the magnetic feature.

# RELATIONSHIP BETWEEN PRODUCTION AND DISTANCE FROM AN AEROMAGNETIC FAULT

Yields are classified in four categories: poor (less than 1 m³/h), mean (from 1 to 2 m³/h), fair (from 2 to 4 m³/h), and excellent (more than 4 m³/h).

Four intervals, large enough to contain a significant number of wells and boreholes were chosen for the distance D to the nearest aeromagnetic fault: less than 300 m, 300 to 600 m, 600 to 1000 m, and more than 1000 m.

Figure 59.16 shows the division of the 182 wells and boreholes into the 16 categories defined by the yield and the distance from an aeromagnetic fault. Figure 59.17 consists of four graphs (one for each interval of the distance D) indicating the percentage of wells or boreholes with poor, mean, fair, or excellent yields. From an examination of Figure 59.17 it is obvious that the yield of wells and boreholes increases as the distance from an aeromagnetic fault decreases. When the distance from a fault decreases from more than 1000 m to less than 300 m the number of wells and boreholes with a poor yield reduces by 50 percent and the number with an excellent yield increases by the factor 2.3.

Another important result is evident in Figures 59.16 and 59.17: the rocks appear to have been fractured up to a distance of 600 m from the faults. The four graphs in Figure 59.17 are clearly divided into two pairs: one corresponds to a distance greater than 600 m and the other to a distance less than 600 m. These results imply that aeromagnetic faults have a tectonic origin and provoke good fracturing of the rocks.

# RELATIONSHIP BETWEEN PRODUCTION AND THE DIRECTION OF FAULTS

To determine if the degree of fracturing corresponding to an aeromagnetic fault depends upon its direc-

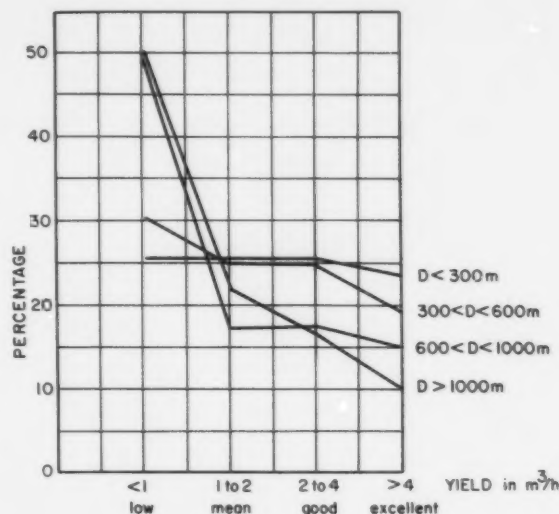


Figure 59.17. Relationship between yield and distance D from an airmag fault.

tion, the two graphs of Figure 59.18 were prepared using the 83 wells and boreholes located within 600 m of the faults. They were divided into two categories: those near a fault oriented north-northeast to east-northeast (43) and those near a fault oriented north-northwest to west-northwest (40). They were then classified according to their production.

For yields up to 4 m³/h the northeasterly faults seem to give better results. For the wells and boreholes of higher yield the results are slightly better along the northwesterly faults. This would appear to imply a greater degree of fracturing in the northwesterly direction, a conclusion that is consistent with the aeromagnetic interpretation which inferred

Distance in m Yield in m ³ /h	D>1000	600<D<1000	300<D<600	D<300	Number of wells
<1	30 wells 50,9%	20 wells 50%	11 wells 30,6%	12 wells 25,5%	73
1 to 2	13 wells 22%	7 wells 17,5%	9 wells 25%	12 wells 25,5%	41
2 to 4	10 wells 16,9%	7 wells 17,5%	9 wells 25%	12 wells 25,5%	38
>4	6 wells 10,2%	6 wells 15%	7 wells 19,4%	11 wells 23,5%	30
Number of wells	59	40	36	47	182

Figure 59.16. Distribution of 182 wells and boreholes in function of their yield and distance D to an Airmag Fault.



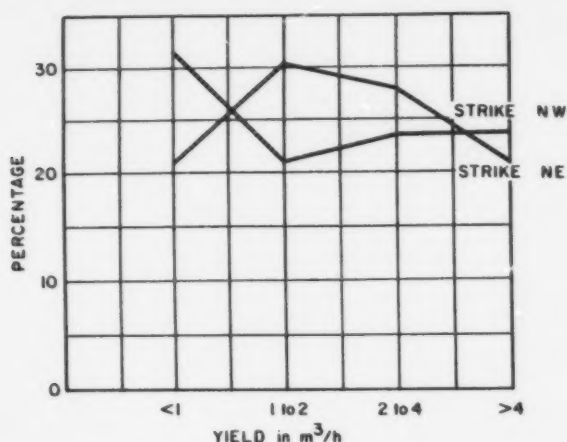


Figure 59.18. Relationship between yield and strike of fault.

that this family was the result of extensional tectonics.

#### RELATIONSHIP BETWEEN PRODUCTION AND THE INTERSECTION OF AEROMAGNETIC FAULTS

It would be logical to infer that at the intersection of faults of different directions there would be an increase in fracturing and a corresponding increase in water yield.

There are only 15 wells and boreholes situated close enough to fault intersections to provide meaningful results. Though this number is too small for valid statistics, it was decided to compare 10 of them located between 600 and 1000 m from fault intersections with 40 others located at the same distance from a single fault. The graphs of Figure 59.19 suggest that by drilling close to a fault intersection the probability of obtaining a yield greater than 1 m³/hr increases between 50 and 80 percent.

#### RELATIONSHIP BETWEEN PRODUCTION AND PROXIMITY TO AEROMAGNETIC DIKES AND CONTACTS

In order to study the relationship between production and location with respect to aeromagnetically interpreted dikes and geological contacts, those within 600 m from a fault, as well as those closer to a fault than to a dike or contact, were rejected. The few remaining wells and boreholes show interesting results.

1. For six wells and boreholes close to dikes oriented north-northeast to east-northeast, the proximity of the dike does not effect production.

However, out of seven wells and boreholes near dikes oriented north-northwest to west-northwest,

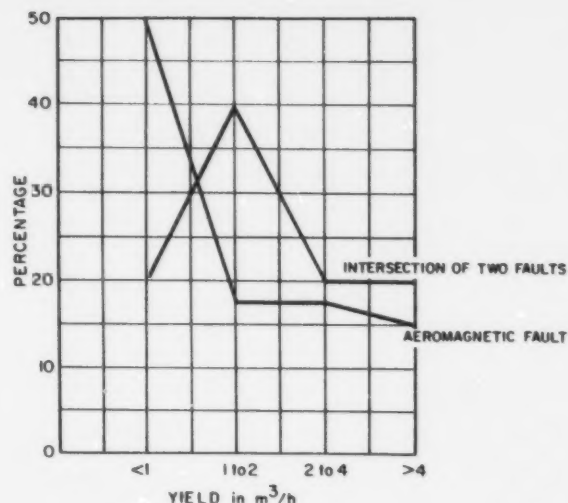


Figure 59.19. Relationship between yield and fault intersections.

six yield over 1 m³/h and five produce more than 2 m³/h. This could imply that the northwest-trending faults are more open than the northeast-trending ones but it seems more probable that the intrusion of the northwest-trending dikes provoked greater fracturing of the rock on both sides. The dikes themselves may also provide barriers to water migration thus increasing the yield on one side or the other.

2. When a well or borehole is situated less than 300 m from a nontectonic geological contact it has a positive effect on the yield. Out of 11 wells and boreholes 8 yield over 1 m³/h.

#### GROUND FOLLOW-UP

As mentioned previously, limited use has been made of aeromagnetic data for groundwater exploration. However, the authors are aware of several programs in Africa and India that are using aeromagnetic interpretations for this purpose. Currently, studies are underway in Burkina Faso to investigate the success rate between drilling programs based on various sets of input data and follow-up methodology (Geirnaert 1987). Examples of field results are not available at the present time. The following results are drawn from an earlier program in western Africa and a current program in eastern India.

#### CASE HISTORY, BOUANRI, BENIN

During 1967 to 1968 F.A.O./U.N.D.P. undertook (Astier 1969) a program of ground geophysics and drilling in Benin based on available geological, photogeological, and other data. Ground magnetic surveys were used to confirm suspected fault lineaments before electrical resistivity methods were applied to pinpoint potential aquifers. Figures 59.20 and 59.21 show the results of surveys in the vicinity

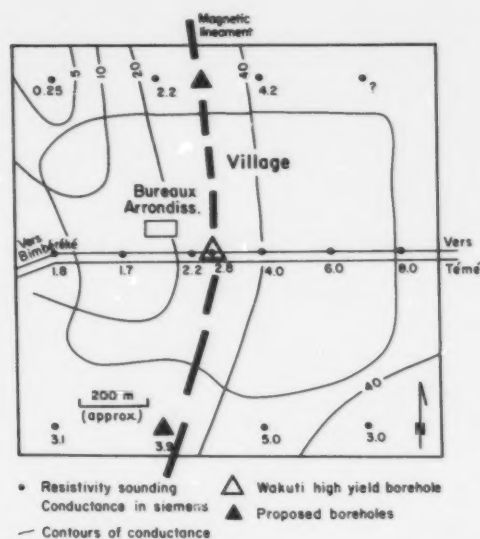


Figure 59.20. Electrical resistivity survey Bouanri (Bimbéréké) Benin.

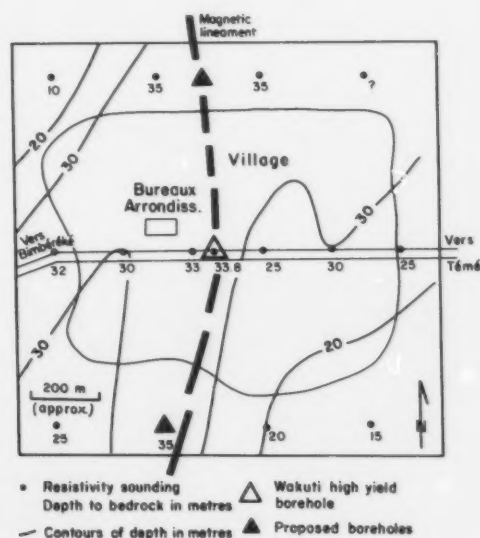


Figure 59.21. Electrical resistivity survey Bouanri (Bimbéréké) Benin.

of Bouanri Village. The ground magnetometer survey confirmed a pronounced lineament which corresponded with a well of exceptionally high yield. The subsequent electrical resistivity survey showed an increase in conductance to the east, probably the result of changes in overburden conductivity. Figure 59.21 indicates that the magnetic lineament coincides with a thickening of the overburden from 20 to 35 m, almost certainly the result of differential

weathering over a bedrock fault. Further drilling was recommended along this lineament.

#### CASE HISTORY, SINGHBHUM, BIHER, INDIA

A joint U.N.D.P./Central Groundwater Board (C.G.W.B.) program (Chandra and Reddy 1987) currently in progress in the State of Bihar was designed to test methods of exploration for various types of groundwater aquifers in both crystalline and sedimentary rocks. Aeromagnetic and photogeological lineaments were followed up on the ground by magnetic, electrical resistivity, and electromagnetic methods. A strong lineament in the Singhbhum metamorphic belt, suspected of being a major shear zone, was followed up by all three methods. The results are shown in Figure 59.22.

The magnetically interpreted faults were confirmed by resistivity and electromagnetics. Two boreholes were sited and both produced artesian flows.

#### SUMMARY

In crystalline and metamorphic areas, aeromagnetic surveys show many faults that are not detected by geological mapping, photointerpretation, or LANDSAT imagery.

In areas of crystalline and metamorphic rocks, proximity to a fault or a dike increases the yield of wells and boreholes (based on statistics from 182 wells/boreholes in Burkina Faso).

The effect of faults and dikes is noticeable to a distance of at least 600 m.

Fault intersections are still more favourable in terms of probable yield.

Direction of faulting and/or dike emplacement may be a factor in influencing yield, probably through the stress pattern during and after faulting/intrusion.

Limited ground follow-up has demonstrated that aeromagnetic faults and dikes can easily be located on the ground and that wells/boreholes sited accordingly are likely to have a much higher than normal yield.

#### CONCLUSIONS

The potential for using aeromagnetic data in groundwater exploration and development in crystalline and metamorphic areas is virtually unlimited. Where aeromagnetic data already exists the cost of siting ground targets is negligible. Where new surveys have to be flown the acquisition and interpretation cost may be of the order of \$20 per km² providing an area of a few thousand square kilometres is surveyed. For smaller areas, ground magnetic surveys may be cost-effective. The authors would encourage groundwater development agencies to consider rural water supplies in terms of using available aquifers in

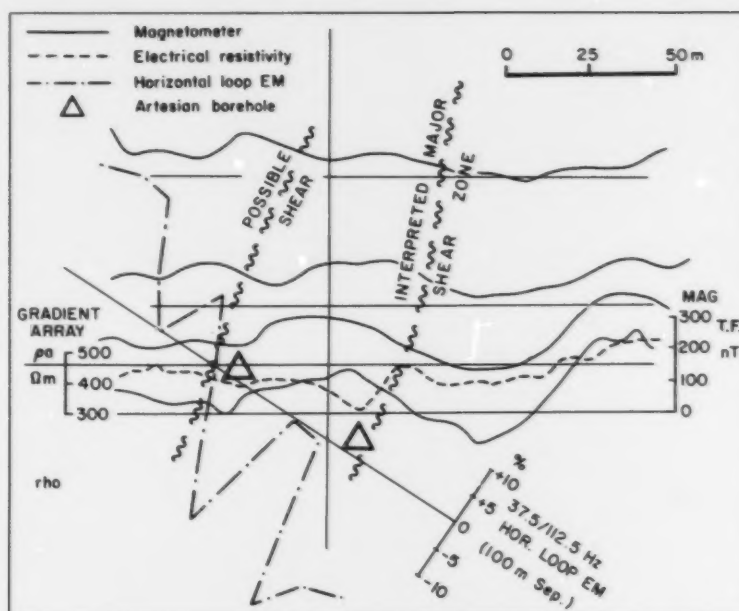


Figure 59.22. Magnetic, resistivity and EM profiles Kudada, Singhbhum District, Bihar, India.

the area rather than looking for lesser yields close to the existing villages. Aeromagnetic surveys in western Africa confirm the conclusions of other studies (International Development Research Centre 1974) that relatively large, untapped groundwater resources are available in many areas of current drought conditions. It is not inconceivable that these aquifers could sustain both human and minor agricultural consumption. Efforts to study these possibilities in Burkina Faso, Bihar, and elsewhere will assist in evaluating the potential of aeromagnetic surveys to meet this critical hydrogeological problem.

## ACKNOWLEDGMENTS

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*HYDROGEOLOGICAL INTEREST OF AEROMAGNETIC MAPS IN CRYSTALLINE AND METAMORPHIC AREAS*  
*J.-L. ASTIER AND N. R. PATERSON*

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# 60. Geochemical Profiles of Deep Groundwater in Precambrian Bedrock in Finland

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## ABSTRACT

The chemical and isotopic compositions of different types of groundwater and their hydrogeological appraisal from 18 exploration drillholes, two drilled wells, and two fracture zones in mines are given. Most of the sampling sites are in Precambrian schist belts, but plutonic rock bodies and an unmetamorphosed sandstone formation were also sampled.

The samples were taken using a tube technique that gives continuous water columns, even from drillholes 1300 m deep. The sampling sites were divided according to the highest observed electric conductivity of the water into four classes: fresh (<100 mS/m), slightly saline or brackish (100 to 500 mS/m), saline (500 to 5000 mS/m), and very saline or brine (>5000 mS/m). The fresh water was usually a Ca-HCO₃ or Na-HCO₃ dominant type. The slightly saline water was either a Ca-SO₄ dominant type or a Na-Ca-Cl type. The saline water was mainly of Na and Ca dominant chloride types, and the very saline water was a Ca-Na-Cl type at the Kotalahti Mine and a Ca-Cl type at Pori (TDS: 120 g/L).

The fresh and brackish water layers have tritium contents ranging from 0.0 TU to 88.1 TU, being in general indicative of recent meteoric water infiltration. In some places, however, the recent freshwater content is negligible. Stable isotope values plot near or along the Global Meteoric Water Line (GMWL) in the  $\delta D/\delta^{18}O$  diagram. Saline and very saline waters commonly have tritium values below 5 TU. The most saline water deviates to the left of the  $\delta D/\delta^{18}O$  GMWL with increasing depth and salinity.

The deepest drillhole containing fresh water bottomed at about 730 m. Saline water layers were encountered from 200 m downwards, and very saline waters at a depth of 250 m. The results indicate that layered groundwater structures with fresh groundwater and a more saline layer underneath exist in many parts of the Precambrian crystalline bedrock in Finland.

## INTRODUCTION

The present project dealing with deep-seated groundwater was initiated by the Geological Survey

of Finland in 1985 as an outcome of plans being drawn up for the deep disposal of nuclear waste in crystalline bedrock. The purpose of the project is to obtain general information on the chemical conditions prevailing in deep-seated groundwaters in different bedrock environments. The accumulating data will serve as a reference basis for nuclear waste site studies, which in Finland and Sweden are mainly directed at granitoidic rock suites.

The results reported so far from drillholes in various parts of Finland (Nurmi *et al.* 1985, in press; Blomqvist *et al.* 1986, 1987) indicate that groundwater composition varies largely from place to place and that layered groundwater structures with fresh groundwater at the surface and a more saline layer underneath are common in crystalline bedrock areas.

The present study reports the chemical and isotopic compositions of different types of groundwater together with their hydrogeological appraisal from 18 exploration drillholes, two drilled wells, and two flowing fracture zones in mines (Figure 60.1). Most of the sampling sites are in, or close to, Proterozoic schist belts lying mainly in mica gneiss-dominant rock environments; but groundwaters from plutonic rock bodies, such as layered mafic intrusions, a monzonite intrusion, an anorogenic rapakivi granite, and a Devonian carbonatite, were also sampled. Samples were also taken from the unmetamorphosed Jotnian sandstone formation in southwestern Finland.

## SAMPLING AND ANALYTICAL METHODS

The sampling method used in the present study was developed at the Geological Survey of Finland to meet the requirements of small-diameter drillholes; for example, holes originally drilled for mineral exploration. The technique used allows a continuous profile of water to be sampled from any drillhole. The water from the hole is received inside a plastic tube with a back-pressure valve at the lower end and shut-off valves every 50 m (Nurmi and Kukkonen 1986). The tube, up to 1300 m long, is raised to the surface with the water column inside, and samples for field measurements and later chemical determinations are taken from the tube water.

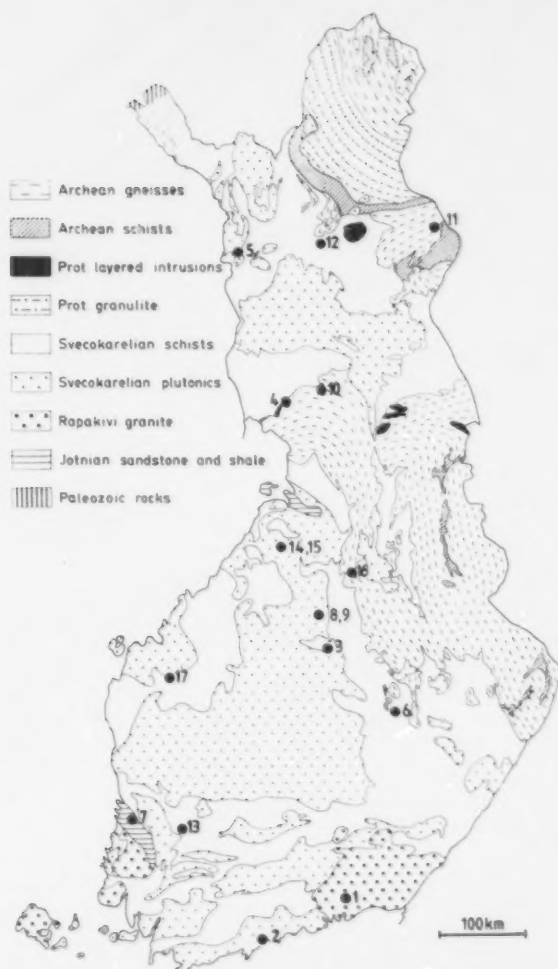


Figure 60.1. The location of the sampling sites studied: drillholes (= Dh), drilled wells, and flowing fracture zones, and the abbreviations used. Geological map compiled after Simonen (1980).

1. Elimäki, Koskisto, drilled well (Eli); 2. Espoo, Otaniemi, Dh R301 (Esp); 3. Keitele, Teerimäki, Dh R494 (Kei); 4. Keminmaa, Sompujärvi, Dh Ki-23 (Kem); 5. Kolari, Hannukainen, Dh R162 (Kol 1) and Dh R197 (Kol 2); 6. Leppävirta, Kotalahti Mine, 745 m level, Dh Ktl-1090 (Kol m. 1) and Dh Ktl-1088 (Kol m. 2); 7. Pori, Pinomäki, Dh Po-1 (Pori); 8. Pyhäjärvi, Kettuperä, Dh PYS-35 (Pyh); 9. Pyhäsalmi Mine, 660 m level, Dh R806 (Pyh m.) and fracture zone at 660 m and 715 m levels (Pyh m. fr.); 10. Ranua, Suhanko, Dh YP-128 (Ran); 11. Savukoski, Sokli, Dh R349 (Sav); 12. Sodankylä, Rajala, Dh R-1 (Sod); 13. Vammala, Suvitie, Dh VM/ST-24 (Vam) and Vammala Mine, 150 m level, Dh OKVA-298 (Vam m.); 14. Vihanti, Suksikangas, Dh 1732 (Vih); 15. Vihanti Mine, 740 m level, Dh 2064 (Vih m.) and fracture zone at 735 m level (Vih m. fr.); 16. Vuolijoki, Honkamäki, Dh R17 (Vuo); 17. Ylistaro, Lahdenkylä, drilled well (Yli).

The sampling procedure, field measurements, and analytical methods used have recently been described in the literature (Nurmi and Kukkonen 1986; Nurmi *et al.*, in press), and the reader is referred to these works. Also, the open hole situation and its effect on sample representativeness has been discussed briefly in the papers above, and a further discussion will be postponed until more informative data on that topic has been received.

## RESULTS OF THE INVESTIGATION

The groundwaters from the sampled drillholes were divided according to the highest observed electric (specific) conductivity of the water into four classes: fresh (<100 mS/m), slightly saline or brackish (100 to 500 mS/m), saline (500 to 5000 mS/m), and very saline groundwater or brine (>5000 mS/m).

Some of the drillholes sampled exhibit a gradual change from fresh or brackish groundwater to more saline water (e.g. Vuolijoki and Ylistaro) but more usually the interface between different water layers is a comparatively narrow zone (e.g. Elimäki, Pori, and Ranua) (Figure 60.2). In some cases (e.g. Pyhäjärvi), several steps are seen in the electric conductivity curves. Although saline water is frequently encountered at shallower depths in coastal areas than inland, there are some areas far inland (e.g. Outokumpu) where the saline groundwater in the drillhole reaches the water table (Blomqvist *et al.* 1987). On the other hand, the freshwater layer may be several hundreds of metres thick in holes drilled along the present shoreline, as in Parainen (Nurmi *et al.*, in press). Hence, there is no clear-cut interdependence between the distance from the present

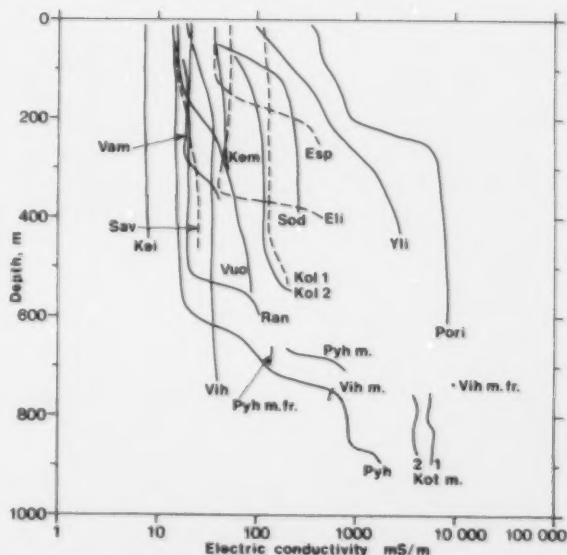


Figure 60.2. Electric conductivity versus depth at various groundwater sites. Abbreviations as in Figure 60.1.

TABLE 60.1. CLASSIFICATION OF GROUNDWATERS ACCORDING TO ELECTRIC CONDUCTIVITY VALUES. ALSO GIVEN ARE EXISTING GROUNDWATER LAYERS AND TYPES WITH CALCULATED TOTAL DISSOLVED SOLIDS (TDS), AND DRILLHOLE LITHOLOGY.

Sampling Site	Total sampled depth m	Ground- water layers m	Electric Conduct- ivity mS/m	TDS g/L	Groundwater type	Lithology
<b>FRESH GROUNDWATER</b>						
Keitele, Teerimäki Dh R494 (Kei)	0-444		8	0.07	Ca-Na-HCO ₃	Mica gneiss and gabbroic rocks
Savukoski, Sokli Dh R349 (Sav)	0-460		16-25	0.14-0.23	Ca-Mg-HCO ₃	Carbonatite
Vammala, Suvitie Dh VM/ST-24 (Vam)	0-368	0-300 330-368	18-22 35-40	0.15-0.16 0.20-0.26	Na-Ca-HCO ₃ Na-Ca-HCO ₃ -Cl	Migmatitic veined gneiss
Vihanti, Suksikangas Dh 1732 (Vih)	0-731		20-41	0.25-0.33	Na-HCO ₃	Mica gneiss and granitoids
Keminmaa, Sompujärvi Dh Ki-23 (Kem)	0-297		38-48	0.36-0.45	Ca-HCO ₃	Gabbroic and ultramafic rocks
Vuolijoki, Honkamäki Dh R17 (Vuo)	0-560	0-180 230-560	16-22 35-88	0.14-0.19 0.30-0.60	Na-Ca-HCO ₃ Na-Ca-HCO ₃ -Cl	Granitic gneiss and amphibolite
Ranua, Suhanko Dh YP-128 (Ran)	0-596	0-510 550-596	20-22 70-105	0.17-0.18 0.40-0.66	Ca-Mg-HCO ₃ -SO ₄ Na-Ca-Cl	Gabbroic and ultramafic rocks
<b>BRACKISH OR SLIGHTLY SALINE GROUNDWATER</b>						
Pyhäsalmi Mine fracture zone VT660 and VT715 (Phy m. fr.)	660, 715		140		Ca-Na-SO ₄ -HCO ₃	Fracture zone (amphibolite, leptyte, and mica gneiss)
Kolari, Hannukainen Dh R162 (Kol 1)	0-545		120-200	1.3-2.5	Ca-SO ₄	Monzonite, diorite, and skarn iron ore
Kolari, Hannukainen Dh R197 (Kol 2)	0-549		60-235	0.63-2.5	Ca-SO ₄	Monzonite, diorite, and skarn iron ore
Sodankylä, Rajala Dh R-1 (Sod)	0-385	0-90 110-385	40-100 150-270	0.21-0.44 1.5-2.0	Ca-Mg-Na-SO ₄ Ca-Na-Mg-SO ₄	Basic and ultrabasic volcanic rocks
Vammala Mine Dh OKVA-298 (Vamm m.)	152		356	1.9	Na-Ca-Cl	Veined mica gneiss
Espoo, Otaniemi Dh R301 (Esp)	0-253	0-150 170-253	38-55 90-435	0.26-0.28 0.48-2.3	Na-Ca-HCO ₃ Na-Ca-Cl	Migmatitic mica gneiss
Elimäki, Koskisto Drilled well (Eli)	0-400	0-350 370-400	42-54 150-490	0.19-0.27 0.78-2.5	Ca-Na-Cl-SO ₄ -HCO ₃ Na-Ca-Cl	Rapakivi granite

Continued

shoreline and the depth of fresh/brackish or saline water interfaces.

The deepest drillhole containing fresh water bottoms at about 730 m (see Figure 60.2). Saline water layers were encountered from 200 m downwards and very saline waters at depths from 250 m. The water quality may change substantially from hole to hole, even when the holes are close to each other, as in the Pyhäjärvi and Vihanti areas. Consequently, the depth of occurrence and quality of water seem to depend mainly on the fracture tectonics and groundwater flow patterns at the study sites.

Only fresh water was found at seven sampling sites. The water was usually a Ca-HCO₃ or Na-HCO₃ dominant type (Table 60.1). Some of these sites seem to be contaminated by surficial fresh water or by water used in drilling. Slightly saline water was found at seven sampling sites from the surface down to 715 m. The water was either a Ca-SO₄ dominant type (Kolari, Pyhäsalmi Mine fracture zone and Sodankylä) or a Na-Ca-Cl type (Elimäki, Espoo and Vammala Mine). Saline groundwater was found at depths of 250 to 900 m at five sampling sites. The waters were Na-Cl (Vihanti Mine), Ca-

TABLE 60.1. CONTINUED.

Sampling Site	Total sampled depth m	Ground- water layers m	Electric Conduct- ivity mS/m	TDS g/L	Groundwater type	Lithology
<b>SALINE GROUNDWATER</b>						
Vihanti Mine Dh 2064 (Vih m.)	742-763		560-570	3.0-3.1	Na-Cl	Mica gneiss, amphibolite, leptonite, and skarn rocks
Pyhäsalmi Mine Dh R806 (Pyh m.)	667-709	667-680 690-709	200-400 600-810	1.5 3.9-5.2	Ca-Na-SO ₄ -Cl Ca-Cl-SO ₄	Amphibolite, leptonite, and mica gneiss
Vihanti Mine fracture zone PL129 and PL131 (Vih m. fr.)	735		975	6.1	Ca-Na-Cl	Analcime granite and pegmatite
Pyhäjärvi, Kettuperä Dh PYS-35 (Pyh)	0-895	0-590 610-710 740-860 870-895	15-22 30-150 500-900 1400-1740	0.14-0.16 0.25-0.84 5.4-10 15-18	Ca-Na-Mg-HCO ₃ Ca-Na-Cl-HCO ₃ Ca-Na-Cl-(SO ₄ ) Ca-Na-Cl ^d	Granitic gneiss, leptonite, cordierite-anthophyllite rocks, and amphibolite
Ylistaro, Lahdenkylä Drilled well (Yli)	0-420	0-250 300-420	100-800 1400-2750	1.4-5.6 11-23	Na-Ca-Cl Ca-Na-Cl	Mica gneiss
<b>VERY SALINE GROUNDWATER OR BRINE</b>						
Kotalahti Mine Dh K11-1088 (Kot m. 2)	745-882		3900-4540	44-48	Ca-Na-Cl	Mica gneiss, amphibolite
Kotalahti Mine Dh K11-1090 (Kot m. 1)	745-897		5600-5900	44-46	Ca-Na-Cl	Amphibolite, mica gneiss
Pori, Pinomäki Dh Po-1 (Pori)	0-613	0-200 250-613	340-840 5000-8400	2.5-5.2 95-120	Na-Ca-Cl Ca-Cl	Sedimentary sandstone

Cl-SO₄ (Pyhäsalmi Mine), or Ca-Na-Cl (Pyhäjärvi, Vihanti Mine fracture zone, and Ylistaro) types. Very saline groundwater was found at depths of 250 to 900 m at two sampling sites: Ca-Na-Cl water at Kotalahti Mine and a Ca-Cl type at Pori. The water in the Pori drillhole has one of the highest salinities so far found in Finland (120 g/L TDS) and is the only brine, *sensu stricto*, of this study.

The vertical distribution of pH, measured immediately after sampling in the field, is presented in Figure 60.3 as two groups: the first group (graph A) comprises drillholes with high pH values or drillholes in which the pH tends to increase in the lower part of the water columns; the second group (graph B) contains drillholes with comparatively low pH values or pH values which tend to decrease with increasing depth. Data from Pyhäjärvi, where the lowest pH values occur in the middle of the water column, are given in both graphs as a reference. There is no clear correlation between pH and salinity, since even in fresh waters the pH values may be comparatively high, as in Keitele, Savukoski, and Vihanti. The pH values tend to increase in the lower, more saline parts of the water columns, as in Kolari, Pyhäjärvi, Ranua, and Vammala, but in some holes the pH values decrease systematically with increasing depth

and salinity (Espoo, Pori, Vuohijoki, and Ylistaro). Consequently, the pH level in individual drillholes is probably affected by several factors, namely, the lithological composition of the rock environment and fracture coatings and fillings, the supply of fresh groundwater from the surface, and the hydrogeological and hydraulic properties of the fractured rock mass concerned.

The Cl contents of the sampled sites are presented versus depth in Figure 60.4. The curves correlate rather well with the electric conductivity curves measured, indicating that chlorides are the main contributors to high conductivity values in groundwaters. The variation in chloride contents is extremely large, from 1 mg/L to almost 100 000 mg/L. The HCO₃ contents, on the other hand, behave more independently, being more or less stable for the whole length of the water column whenever the Cl values are low (less than 200 mg/L, see graph A in Figure 60.5). In boreholes with higher Cl contents, the HCO₃ values decrease with increasing depth (see graph B in Figure 60.5). Hence the Cl and HCO₃ curves for some sites are like mirror images of each other as in the Espoo and Ylistaro drillholes. The highest HCO₃ contents were found in drillholes containing fresh groundwater, es-



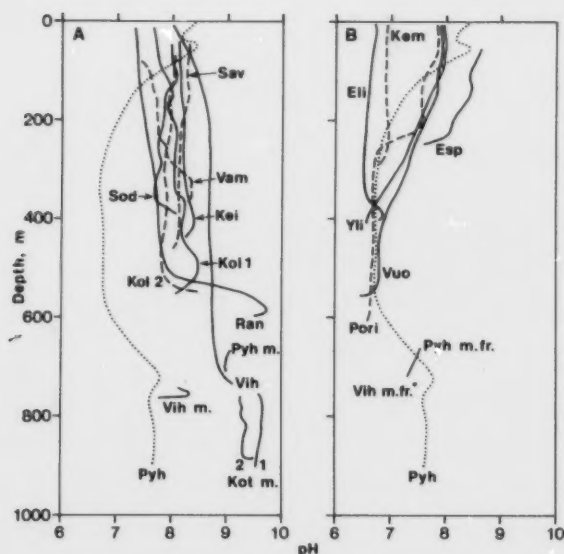


Figure 60.3. pH versus depth at various groundwater sites. The pH curves are presented in two graphs: A) high pH or pH values which tend to increase in the lower parts of the water columns and, B) comparatively low pH or pH values which decrease with increasing depth. The curve for the Pyhäjärvi drillhole (Pyh) is given in both graphs for reference. Abbreviations as in Figure 60.1.

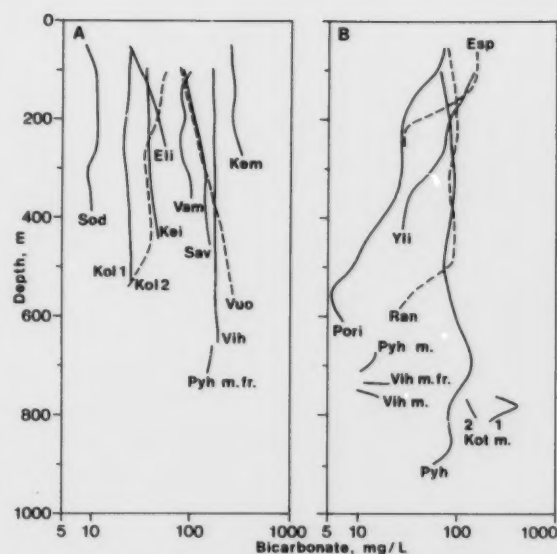


Figure 60.5. Bicarbonate versus depth at various groundwater sites. Abbreviations as in Figure 60.1.

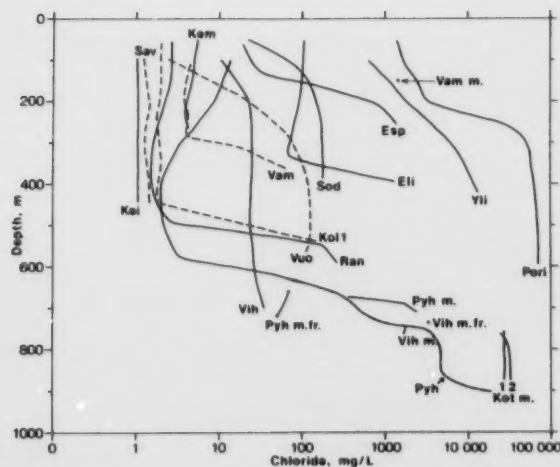


Figure 60.4. Chloride versus depth at various groundwater sites. Abbreviations as in Figure 60.1.

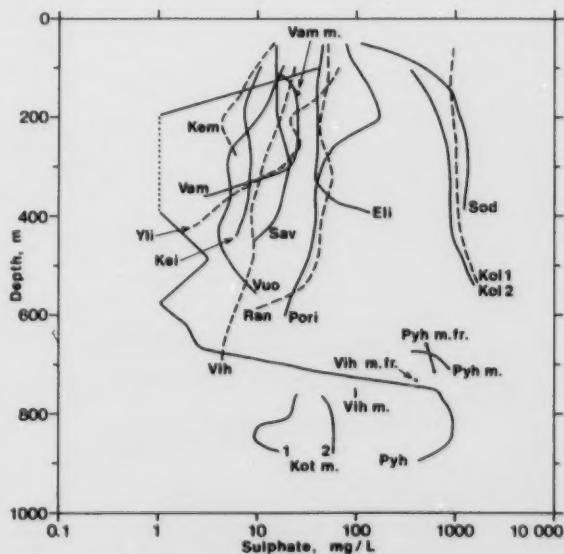


Figure 60.6. Sulphate versus depth at various groundwater sites. Abbreviations as in Figure 60.1.

pecially in gabbroic and carbonatitic massifs and in an alkalic gneiss suite (Keminmaa, Savukoski, and Vuolijoki), but quite high  $\text{HCO}_3$  contents were also encountered in some mica gneiss areas (e.g. Vihanti). The lowest  $\text{HCO}_3$  contents were found in the  $\text{SO}_4$  dominant waters of Sodankylä and Kolari and in the brine of Pori.

The highest  $\text{SO}_4$  contents, about 1000 mg/L, were found in the Sodankylä hole drilled in basic and ultrabasic volcanics, and in the Kolari drillholes, where a skarn iron ore with anhydrite veins were met (Figure 60.6). Other high sulphate values were found in the Pyhäjärvi mining area (Kettuperä and Pyhäsalmi Mine), where the drillholes intersect schists and gneisses hosting sulphides. Consequently, it seems plausible that high sulphate values in waters may be due to relatively easily soluble sulphate minerals or, in the vicinity of mines, to oxydized sulphide minerals.

However, in most of the drillholes the  $\text{SO}_4$  contents decrease regularly with increasing depth (e.g. Pori, Ranua, Vihanti, and Ylistaro), possibly as a result of the more reducing conditions deep down in the bedrock.

Calcium and sodium are the most abundant cation components of fresh and slightly saline groundwaters, Na being dominant in mica-rich gneissic areas, and Ca in basic rocks. Calcium contents increase with increasing salinity and depth, the increase being most pronounced in the saline waters and brines at Pori, Pyhäjärvi, and Ylistaro (Figure 60.7, see also Nurmi *et al.*, in press). This feature is common in the Canadian Shield brines (see e.g. Frape and Fritz 1982; Frape *et al.* 1984).

Strontium contents in fresh and slightly saline waters are usually below 5 mg/L. However, they correlate well with those of Ca, and increase with increasing salinity. The highest contents were found at the bottom of the Pori drillhole (550 mg/L), which is where the highest Li and Ba contents so far recorded in Finnish groundwaters (13.5 and 8.9 mg/L, respectively) have also been found.

Magnesium contents, too, tend to increase with growing salinity and depth in the most saline groundwaters (Figure 60.8). In many cases, however, the magnesium contents are more or less constant and sometimes even decrease with increasing depth and salinity, as in Kolari, Ranua, and Vammala. The range of Mg is from 0.2 to 300 mg/L.

Bromine and iodine are conservative elements and increase in concentration together with Cl. The highest Br contents were found in the most saline groundwaters (Kotalahti Mine, Pori, Pyhäjärvi, and Ylistaro), with the extreme value of 550 mg/L in Pori brine (Figure 60.9). In slightly saline or fresh groundwaters the bromide contents are generally below 1 mg/L.

Iodide contents, which were also highest in the Pori brine (1.1 mg/L), usually occur only in concentrations of a few micrograms.

The fluoride concentration is generally below 1 mg/L (Figure 60.10). The highest values determined so far (3.2 mg/L) were found in an alkalic granitic gneiss (Vuolijoki) and a rapakivi granite (Elimäki). In both places the rock is fairly rich in easily soluble fluorite. The lowest contents, on the other hand, were found in mafic or ultramafic rock environments, e.g. in Keminmaa, Kotalahti Mine, and Ranua drillhole waters, where some of the concentrations are below the detection limit (0.1 mg/L). Comparatively high concentrations were also found in groundwaters in monzonite granite in Kolari, and in the upper part of the Pori drillhole, where the bedrock is composed of unmetamorphosed Precambrian sandstones and slates.

Iron and manganese contents are normally low or below detection limits. In a few drillhole waters the concentrations were, however, quite high, as in fresh water in Keminmaa (6.6 mg/L Fe, 0.6 mg/L Mn), Pyhäjärvi (11 mg/L Fe, 1.2 mg/L Mn), and Vuolijoki (23 mg/L Fe, 0.45 mg/L Mn), and in saline water in Pori (5.4 mg/L Fe, 6.5 mg/L Mn) and Ylistaro (2.7 mg/L Fe, 2.5 mg/L Mn). In the Pori, Vuolijoki, and Ylistaro drillholes the concentrations were highest in the bottom part of the water columns, where the lowest pH values (about pH 6.7) were found. In the majority of the sampled sites the Zn, Cu, Ni, Co, Cr, Pb, V, Ti, Mo, and Cd contents are low or even below detection limits. This is not unexpected since many drillhole waters are fairly alkaline (pH 8 to 10) and the environment is strongly reducing. The highest Zn and Cu contents (0.18 mg/L Zn and 0.13 mg/L Cu) were found in the upper portion of the highly saline brine in Pori, where the pH is 7 or just below 7.

The interdependence between the main cations and chloride was studied at selected sample sites by using correlation diagrams for fresh or slightly saline groundwaters (Figure 60.11) and saline groundwaters or brines (Figure 60.12). In fresh or slightly saline waters, there is a good correlation between Na and Cl contents (see Figure 60.11). Ca contents versus Cl increase strongly only in the Kolari drillhole water and to a lesser extent in the Sodankylä water. In the other drillholes, Ca contents seem to vary independently of Cl contents. The same holds for Mg and K; the only exception being the Sodankylä drillhole waters.

The above correlations between the main cations and Cl do not imply an overall uniform interaction between water and the surrounding wall rocks in fresh and slightly saline waters. The Na contents increase in equal manner in the waters of different lithological environments. On the other hand, the high Ca, Mg, and K versus Cl ratios found in some drillhole waters seem to indicate local water-rock interaction. The high Ca concentrations in the Kolari

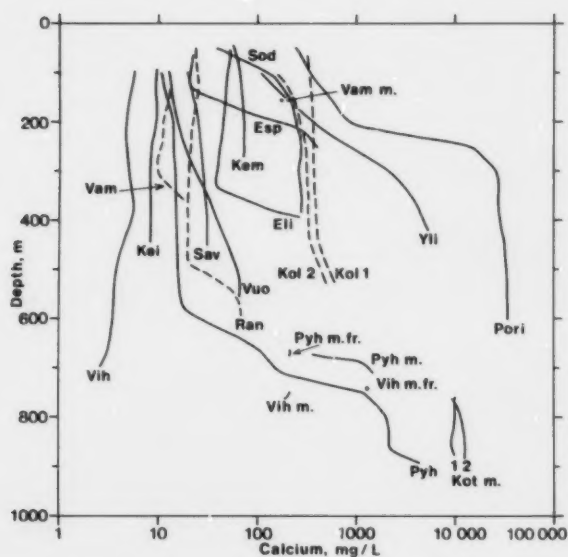


Figure 60.7. Calcium versus depth at various groundwater sites. Abbreviations as in Figure 60.1.

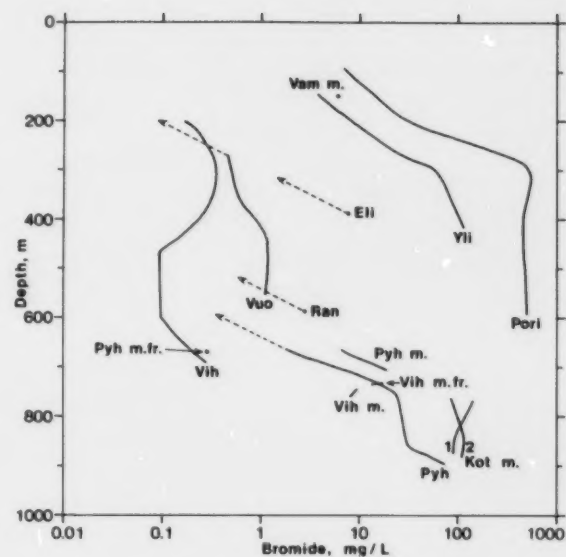


Figure 60.9. Bromide versus depth at various groundwater sites. Abbreviations as in Figure 60.1.

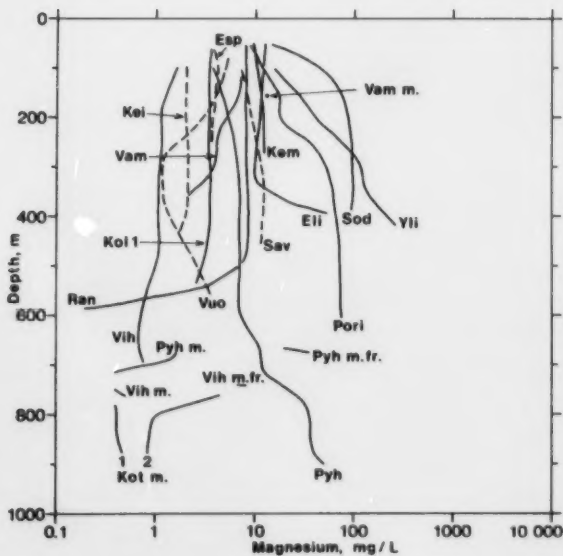


Figure 60.8. Magnesium versus depth at various groundwater sites. Abbreviations as in Figure 60.1.

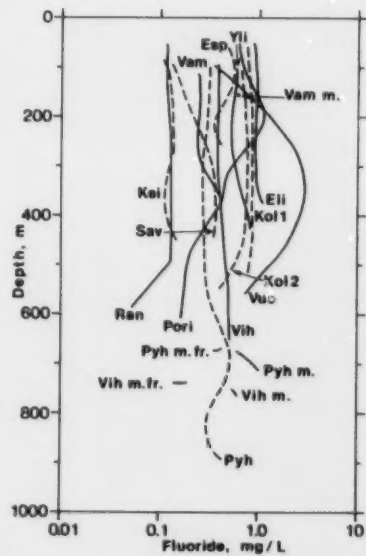


Figure 60.10. Fluoride versus depth at various groundwater sites. Abbreviations as in Figure 60.1.

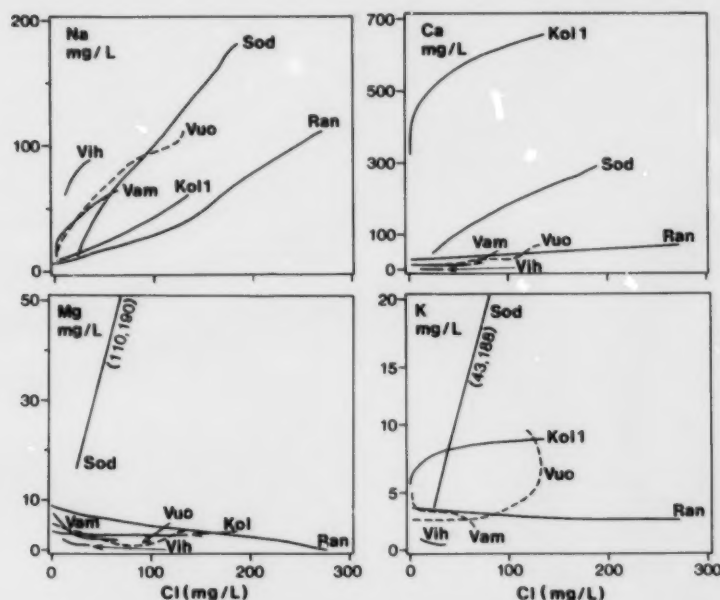


Figure 60.11. Na, Ca, Mg, and K concentrations versus chloride for fresh or slightly saline waters. The numbers in the brackets give the end values for the correlation curves which continue off scale. Abbreviations as in Figure 60.1.

drillhole can be attributed to the presence of Ca-sulphate veins in the surrounding rocks, and the Mg and K concentrations in the Sodankylä drillhole water probably reflect the surrounding Mg-rich greenstones and the secondary mineral reactions involved in water-rock interaction.

In the correlation diagrams for saline waters or brines the seawater dilution line (SWDL) is also presented (see Figure 60.12), and comparisons are made to evaluate the possible effect of seawater on groundwater salinity. Most of the drillhole waters studied are depleted in Na with respect to seawater composition. The correlation curves for the Pori, Pyhäjärvi, and Ylistaro drillhole waters resemble each other, whereas the Kotalahti waters have somewhat higher Na/Cl values. Calcium is more strongly enriched in saline groundwaters than it is in seawater; the same tendency prevails in all the waters studied. The highest Mg contents, with the Mg/Cl ratio close to that of seawater, were found in the Ylistaro waters; the other drillhole waters are strongly depleted in Mg. In the K diagram of Figure 60.12 the upper part of Pyhäjärvi drillhole water coincides with SWDL whereas the lower part deviates strongly from the SWDL. Also, the Pori drillhole water is strongly depleted in K. Bromide and iodide have relatively higher concentrations in saline groundwaters or brines than in seawater. As a conservative element, Br has been used in deciphering the possible seawater origin of old saline groundwaters or brines. The Br/Cl ratios in the upper part of the Pori, Pyhäjärvi, and Ylistaro drillhole waters

are close to those of seawater but in the deeper parts the ratios deviate more from the trend of the SWDL.

The results presented above do not favour a marked marine contribution to salinity in the drillhole waters studied, even though the cation to chloride ratios are somewhat similar to those found in marine environments. Hence, it seems plausible that diversified water-rock interaction processes have a stronger impact on the distribution of cations in water than an ancient seawater source.

The tritium values of the groundwaters studied vary from 0.0 to 88.1 TU (Figure 60.13). The values are generally highest in the uppermost freshwater layers, tending to decrease downwards with increasing salinity and depth. The highest tritium values were found in the waters of relatively shallow drillholes in Elimäki, Keminmaa, and Savukoski; the lowest values were in the saline waters of Kotalahti, Pori, and Ylistaro. There are, however, numerous exceptions to the rule. In some drillholes the tritium values in fresh water are already very low in the surficial parts of the drillhole, as in Ranua, indicating that surface water infiltration and groundwater circulation are relatively slow. On the other hand, high tritium values are also found in some waters deep down in drillholes, e.g. at 540 m in Vuolijoki and at 550 m in Pyhäjärvi. In the Pyhäjärvi hole there are also somewhat elevated tritium values at the bottom of the hole (840 to 900 m). These findings can be explained in many ways, e.g. by flow of surficial water down along the drillhole or along fracture



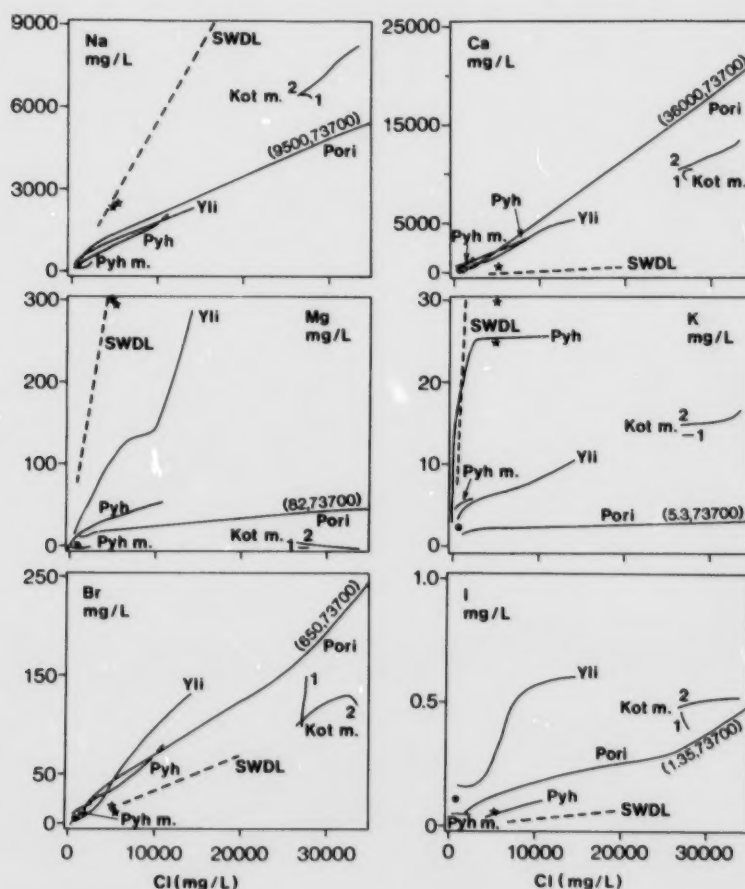


Figure 60.12. Na, Ca, Mg, K, Br, and I concentrations versus chloride for saline waters or brines. For comparison, the old saline groundwater from the Hästholmen site (★), Gulf of Finland, and the slightly saline groundwater from Stripa (●), Sweden, are also presented. Hästholmen site: Y1, 191.8 to 195.3 m, 21.3.1983 and 8.1985 (Nordstrom 1986) and Stripa: VI, 410 to 506 m, 19.8.1981 (Nordstrom et al. 1985). Other explanations as in Figure 60.11.

zones, as indicated by temperature measurements in the drillhole of Pyhäjärvi (Kukkonen, in preparation), where the flow is probably affected by pumping in the mine lying in the same schist formation some 2 km farther south. The presence of old residues of drilling fluids can explain high tritium values, when the flow near the drillhole bottom is negligible.

The distribution of the environmental stable isotopes,  $\delta^2\text{H}$  ( $\delta\text{D}$ ) and  $\delta^{18}\text{O}$ , versus depth is presented in Figure 60.14. In some of the sampled drillholes  $\delta\text{D}$  and  $\delta^{18}\text{O}$  values diminish slightly with increasing depth and salinity, as in Elimäki and Kolari. In some holes, e.g. in Pyhäjärvi and Ylistaro, the changes are not systematic. In the Pori drillhole, there is a dramatic increase in heavy isotope contents from the surficial part of the water column to the underlying more stagnant and very saline parts. This is unequivocal proof of the difference in geochemical evolution of the water layers concerned. In the

Kotalahti Mine drillhole waters, the isotope values resemble those of the Pori drillhole.

The stable  $\delta$ -isotope values are also presented as  $\delta\text{D}/\delta^{18}\text{O}$  diagrams in two groups: fresh, brackish, or slightly saline groundwaters (Figure 60.15) and saline and strongly saline groundwaters or brines (Figure 60.16). Fresh and slightly saline groundwaters plot along the GMWL, with samples from the northern part of the country (e.g. Kolari and Savukoski) clustering at the lower end of the line. The most saline groundwaters (Kotalahti Mine, Pori, and Ylistaro) deviate to the left of the GMWL with increasing salinity and depth. In the Pori drillhole the upper brackish water is depleted in heavy isotopes, and the lower brine shows the heaviest isotopic composition yet found in this country. In the drilled well at Ylistaro, the deviation from the GMWL is not very pronounced but the direction is perpendicular to the GMWL.

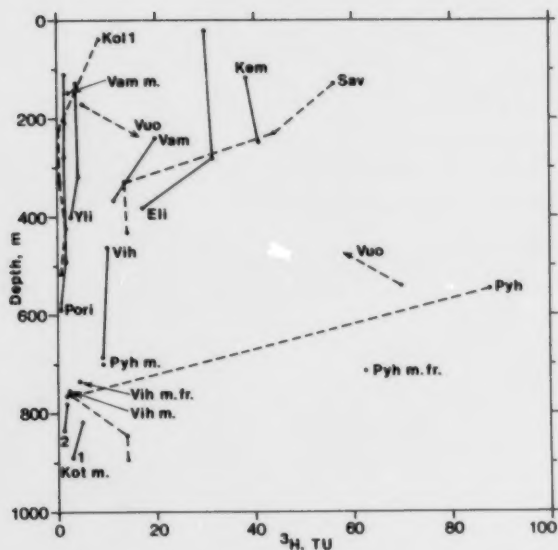


Figure 60.13. The distribution of tritium ( $^3\text{H}$ ) in groundwaters in selected drillholes. Abbreviations as in Figure 60.1.

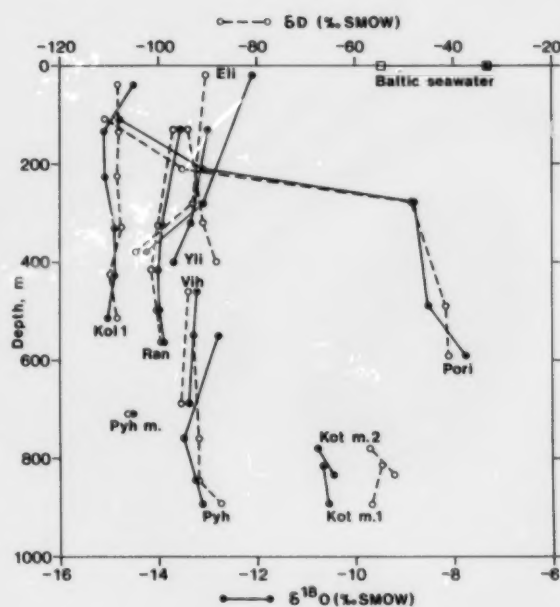


Figure 60.14. The distribution of  $\delta\text{D}$  (‰ SMOW, upper scale, open circles and dashed lines) and  $\delta^{18}\text{O}$  values (‰ SMOW, lower scale, black dots and continuous lines) versus depth for selected drillholes. Abbreviations as in Figure 60.1.

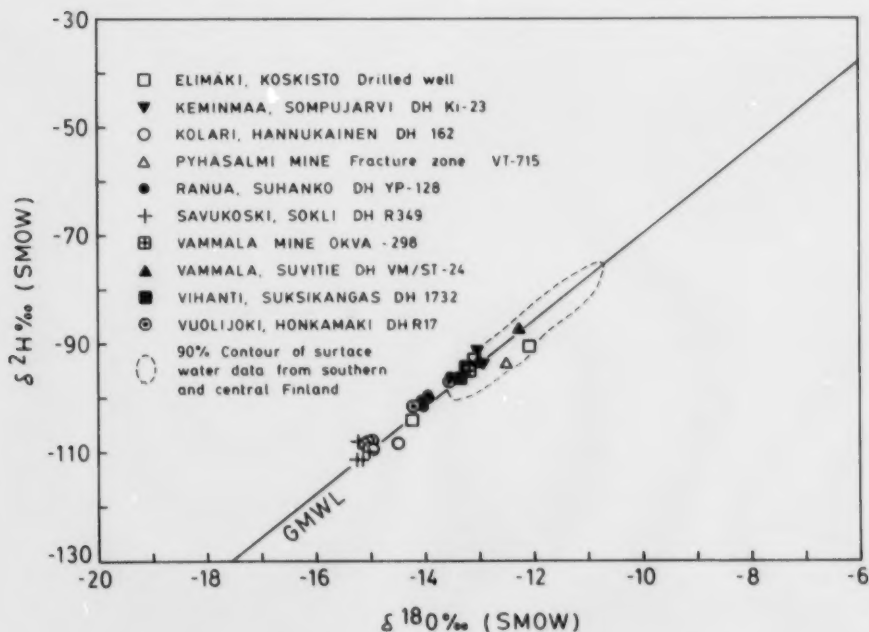


Figure 60.15. Oxygen-18 and deuterium plot for groundwaters from the sampling sites containing fresh or slightly saline waters.

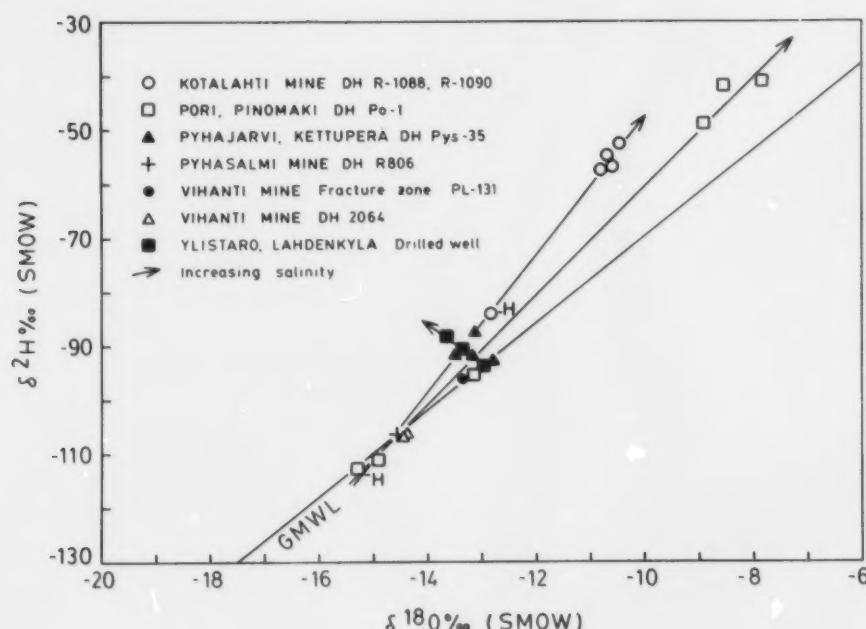


Figure 60.16. Oxygen-18 and deuterium plot for groundwaters from the sampling sites containing saline groundwaters or brines. The sample marked H is from Hyyppä (1986).

## CONCLUSIONS

The results obtained show that saline groundwaters are common in crystalline bedrock areas, and that such waters can be found everywhere at reasonable depths (from 500 m downwards). The fresh water in the bedrock is mainly a Na or Ca bicarbonate type, whereas the slightly saline and saline waters are Na and Ca chloride types. The only brine found so far (in Pori) is a Ca-Cl type. Locally the water may be rich in  $\text{SO}_4$  owing to relatively easily soluble anhydrite and/or altered sulphide minerals. Tritium contents are, with a few exceptions, low at great depths and in some places even in surficial parts of the water column, demonstrating that groundwater infiltration is relatively slow in these places. Locally, however, high tritium contents are encountered down to several hundred metres in the bedrock. In most cases the results could be due to flow along the holes, or to contamination by mining or the drilling of the holes, but infiltration along fractures cannot be excluded. Stable isotope values show that the majority of the saline waters plot along the GMWL. The most saline waters and brines, however, are strongly enriched in heavy isotopes, clearly demonstrating that these waters have undergone a different geochemical evolution.

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# **National/International Programs: Their Roles and Achievements**

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# 61. Government Geoscience and Exploration

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## ABSTRACT

To govern, governments require information. Geoscience information plays two roles: 1) it is required for the development of sound policies concerning resource development, public safety, national security, and sovereignty; and 2) when made available as a public good, it serves as an instrument for the implementation of such policies.

To respond to specific geoscience information requirements, governments need an adequate national geoscience knowledge base. The national geoscience knowledge base is a unique national resource which needs to be continually replenished as new concepts, interpretations, and information becomes available.

Among the kinds of geoscience information that governments provide to facilitate exploration, two are fundamental. The first, information on the geological environments in which resources occur and the processes by which they form, is the cumulative product of various kinds of survey activities. The second, exploration technology, results from the development, testing, and application of geological, geophysical, and geochemical techniques to detect the presence of mineral deposits.

Exploration in the future will be increasingly influenced by technologies which allow integration and analysis of multiple data sets derived from a variety of geoscientific investigations, and by a multidisciplinary team approach involving joint ventures with industry and universities to meet the financial and human resource requirements of "big science".

## INTRODUCTION

To govern, governments require information.

Geoscience information plays two roles. It is required by governments for the formulation of policies concerning resource development, public safety, national security, and sovereignty; and, when made available as a public good, it can serve as an instrument for the implementation of public policies. Provision to the public of geoscience information bearing on natural resource availability, on geophysical and geological hazards and constraints to resource development and other engineering works, and on changes in the environment, is a well-established method of promoting regional economic development and public safety.

Geoscience information has been systematically acquired and used for public policy purposes by ma-

jor governments throughout the world since the middle of the nineteenth century. Following the establishment of the Geological Survey of Great Britain in 1835, as an agency of the Government of the United Kingdom, the number of countries with government agencies dedicated to geoscience has grown to more than 150 worldwide. These agencies simultaneously provide geoscience information and advice to government, and publish geoscience information in order to make it available as a "public good" that will help meet the policy objectives of the government in the fields of economic development, public safety, protection of the environment, national security, and sovereignty.

The nature of the involvement of national geoscience agencies in resource exploration is as varied as are the countries themselves. In some countries, there are no private companies and exploration is carried out exclusively by the national geoscience agency. In others, including many in western Europe, exploration is conducted by both the national geoscience agency and private companies. In Canada, management of mineral resources is the responsibility of the provinces and mineral exploration and development is conducted by private companies. Accordingly, the role of the Geological Survey of Canada (GSC) in mineral exploration is an indirect one. Although the following discussion of the role of the Geological Survey of Canada in exploration deals specifically with the Canadian situation, many of the themes will find universal application.

## THE GEOSCIENCE KNOWLEDGE BASE

The mission of the Geological Survey of Canada has remained essentially unchanged since it was founded in 1842. The Geological Survey of Canada exists to ensure the availability of geological, geophysical, and geochemical knowledge, technology, and expertise concerning Canada, including the deep earth and the offshore territory, to fulfill a number of national requirements including the effective exploitation of mineral and energy resources.

The key to fulfilling these national requirements is an adequate national geoscience knowledge base (Figure 61.1). The geoscience knowledge base is a unique national resource; it comprises all the geoscience knowledge, technology, and expertise that is required for the formulation and effective implementation of sound policies on resource development, public safety, national security, and sovereignty. Comprehensive up-to-date geoscience information covering the whole country is generally a basic requirement for effectively governing the coun-



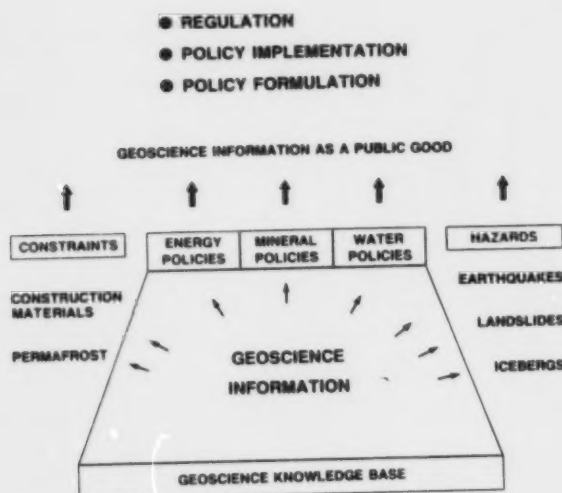


Figure 61.1. The flow of information from a single geoscience knowledge base to various policy areas (after Price 1986).

try. It involves a sustained national effort in geoscience research.

Research in the geosciences, unlike that in chemistry or physics, is site specific. The same observations on a chemical reaction or on the behaviour of subatomic particles or other physical phenomena can be made anywhere; but studies of the earth generally involve making observations at specific places on the earth. The observation relates to the whole earth, but applies to a specific location on the earth. Thus, geoscience observations made within a specific country become a unique resource of that country because they pertain specifically to that country. It is this fundamental difference with respect to observations in other branches of science that accounts for the fact that geological, geophysical, and geochemical research activities are frequently referred to as surveys rather than research. Nevertheless, most geoscience "surveys" are basic scientific research; they provide new scientific observations, new scientific hypotheses, and critical tests of existing scientific hypotheses. They also provide the building blocks of the national geoscience knowledge base.

The national geoscience knowledge base is a dynamic entity. It loses value with time unless replenished by continually being updated and improved through new research. A dynamic geoscience knowledge base is the source from which geoscience information is extracted to meet specific policy and operational requirements. These may range from information about permafrost required for economic development in the far north, to information about potential natural hazards, to public safety in the south, such as earthquakes, landslides, and volcanic eruptions.



Figure 61.2. Policy formulation and the National Geoscience Knowledge Base (after Price 1986).

Geoscience information flows into many areas of policy environment including mineral policy, energy policy, water policy, transportation policy, public safety, national security, and regional economic development. It flows out of the policy environment as a "public good". Moreover, a large component of the geoscience information flow is generated specifically to foster mineral and mineral fuel exploration and development. This generation of new geoscience information helps to replenish and improve the national geoscience knowledge base. Figure 61.2 illustrates how the national geoscience knowledge base forms the reservoir, which on the one hand feeds a variety of activities in the system, and on the other hand, is replenished from a variety of activities. Of particular significance is the two-way flow of information from and to industry, and from and to the various institutions of the country involved in geoscience, including provincial or state geological surveys and the universities.

## THE CANADIAN CONTEXT

Geoscience information is of particular significance in Canada because of the importance of resources in the Canadian economy. Mineral production (including fuels) accounts for 10 percent of the Canadian Gross National Product (GPN), 15 percent of total capital investment, and 20 percent of all exports. Canada ranks first in the world in the production of uranium and zinc, second in nickel, gypsum, asbestos, sulphur, and potash, and third in gold, platinum metals, titanium concentrates, and cadmium.

Canada's land area is nearly ten million square kilometres, second only to the Soviet Union (Table 61.1). It comprises about seven percent of the world

TABLE 61.1. SOME CANADIAN STATISTICS.

Geography	
Landmass	$9.97 \times 10^6 \text{ km}^2$
Offshore	$6.50 \times 10^6 \text{ km}^2$
Total Territory	$16.47 \times 10^6 \text{ km}^2$
Population	$25.2 \times 10^6$
Population Density	$2.5 / \text{km}^2$
Value of Mineral Production (1986)*	
Metals	$\$ 8.94 \times 10^9$
Non-Metals	$\$ 4.38 \times 10^9$
Structural Materials	$\$ 2.20 \times 10^9$
Other Minerals	$\$ 0.04 \times 10^9$
TOTAL	$\$ 15.66 \times 10^9$

* excluding petroleum and natural gas

total. The ocean-covered areas over which Canada exercises jurisdiction add another six million square kilometres to that total area.

Canada is well endowed geologically. Rocks favourable as hosts for metallic and nonmetallic mineral deposits occur at or close to the surface over a very high proportion of Canada's land area. The Canadian Shield, by far the largest Precambrian Shield in the world, dwarfs the mineral-rich Precambrian shields of southern and central Africa, Australia, Brazil, the Baltic, and Siberia. British Columbia, the Yukon, and Alberta contain a major segment of the resource-rich Cordilleran mountain belt that stretches southward from Alaska, through the United States, Mexico, and Central America to form the backbone of South America. The Atlantic Provinces and Québec contain a major segment of the Appalachian-Caledonian-Hercynian mountain belt that has been the source of the mineral wealth of the eastern United States and western Europe. The high Arctic is, like Antarctica, a new frontier which offers promise of resources for the future.

Much of Canada's vast land area is virtually unexplored; but even more significant is the fact that major new orebodies continue to be found close to established transportation routes and mining camps in the southern fringe of Canada, where mineral exploration has been underway for the longest time and has been most intensive. The discovery of the world-class gold deposits at Hemlo, Ontario in 1980, literally underneath the Trans-Canada Highway, provides the most spectacular recent example. Canada's mineral resource potential is probably greater than that of any nation in the world, with the possible exception of the Soviet Union. This resource potential is reflected in the vibrance of the Canadian mineral exploration industry, in which expenditures totaled more than \$490 million in 1985, excluding petroleum and natural gas.

## GEOSCIENCE FOR EXPLORATION

Having considered the role of geoscience information in public policy formulation and the responsibility of government geoscience agencies to build and maintain the national geoscience knowledge base, it is appropriate to examine the role of government geoscience in resource exploration. As emphasized above, the role of the Geological Survey of Canada in exploration is not a direct one.

Among the variety of streams of geoscience information provided by governments to facilitate the exploration for mineral resources, two are fundamental. The first is information on the geological environments in which resources occur and the processes by which deposits form. This is the cumulative product of various kinds of survey activities including bedrock and surficial mapping, tectonic syntheses, mineral deposits and metallogenic research, sedimentary basin analyses, and so on. The second stream of geoscience knowledge fundamental to exploration derives from the development, testing, and application of geophysical, geochemical, and geological exploration methods to detect the various physical and chemical signatures of mineral deposits.

## REGIONAL GEOSCIENCE SURVEYS

A large part of the traditional geoscience work of the GSC may be described as regional and special surveys. This includes the ongoing 1:250 000 scale geological mapping programs, particularly in the Cordillera and northern Canadian Shield, the systematic geophysical and geochemical surveys of various parts of the country, and the geological and tectonic compilations and syntheses that incorporate these as well as the efforts of provincial agencies and others. In recent years, much of this survey work has been conducted jointly and in parallel with the provinces under various Federal-Provincial Mineral Development Agreements.

New technology continues to transform dramatically the nature, scope, and pace of these activities. Just as aerial photography and helicopter transportation revolutionized geoscience surveys in the second and third quarters of this century, computer technology is a dominant force for change in the final quarter of the twentieth century.

One relatively new development is the application of airborne radiometric surveys to geological interpretations (Darnley and Ford, *see* Paper 21, this volume). The use of a three component ratio technique on computer-printed coloured maps to portray the relative proportions of potassium, uranium, and thorium, is a powerful new technology which can augment traditional geological mapping. The distribution of the three radioelements can be used to delineate geological contacts, structural elements, and even internal lithological variations which may not be evident in traditional geological mapping. This is illustrated by the recent survey of the Win-

nipeg River district of Manitoba (Plate 61.1, see Colour Folio near back of book). Distinctive radioelement patterns characterize the principal geological elements of the area including the Bird River greenstone belt, the various granitic stocks and batholiths, the Manigotagan gneiss belt, and the Greer Lake and Bernic Lake pegmatites (the latter hosting the Tanco tantalum–lithium–cesium mine) (Geological Survey of Canada 1987a). It is interesting that the Lac du Bonnet and Maskwa Lake Batholiths are similar in having large areas with sub-equal proportions of uranium and thorium and relatively less potassium, whereas the Marijane Batholith is zoned from a relatively uranium-rich margin toward a potassium-rich core. Another unexpected result was the distinctive band of relative uranium enrichment in the Manigotagan gneiss belt at its contact with the Bird River greenstone belt.

For many years, the Geological Survey of Canada has been investigating and mapping Canada's offshore territories, particularly in the context of potential oil and gas development. More recently, we have undertaken mapping and other research on the Juan de Fuca spreading ridge system off Canada's west coast from the standpoint of metallic mineral resource potential (Figure 61.3).

These studies, conducted in collaboration with colleagues from Canadian universities, have already resulted in the discovery of several significant massive sulphide deposits on the seafloor (Davis *et al.* 1987). For example, one of the eight sulphide mounds at Middle Valley is estimated to contain many tens of millions of tonnes of sulphide grading about 4 percent zinc. There are seven other mounds which remain to be investigated. Although it is unlikely that these deposits will be mined in the foreseeable future, because of their location and the substantial resources on dry land, they do provide new insights on the ore-forming processes, and this will result in improved guidelines for the exploration for ancient deposits in onshore areas.

This work involves a panoply of new technologies including direct observation using submersibles or towed camera systems, dredging, core drilling, and geophysical techniques. For example, Figure 61.4 is a "side-lit" bathymetric map of Explorer Ridge showing the location of sulphide mounds in the axial graben. The map also illustrates the episodic nature of ridge development with repeated cycles of prolific volcanism giving rise to the prominent ridges, spreading, flooding of the resultant valley by sheet flows, and renewed excessive volcanism. Figure 61.5 is a side scan sonar image of Endeavor Ridge showing an intensely fissured and faulted central graben, bulbous mounds of pillowed flows on the west flank, and sediment cover at the base. Other new technologies associated with this program include the tethered drill developed jointly by the Geological Survey of Canada and Dalhousie University, and the ROV (Remotely Operated Vehicle)

currently being developed under the direction of the Canadian Department of Fisheries and Oceans with the participation of the GSC.

Another recent initiative is GLIMPCE (Great Lakes International Multidisciplinary Project on Crustal Evolution), a joint project involving the Geological Survey of Canada, the U.S. Geological Survey, several state and provincial geological surveys, and representatives of Canadian and U.S. universities. GLIMPCE is an attempt, through a combination of multichannel marine seismic profiling technology applied on the lakes, land-based seismic recording, systematic gravity and aeromagnetic surveys and geological synthesis, to map and interpret the Precambrian crust beneath the Great Lakes Basin and surrounding regions. It has already yielded valuable new insight into the deep structure of the mid-continent rift system and the Grenville Front tec-

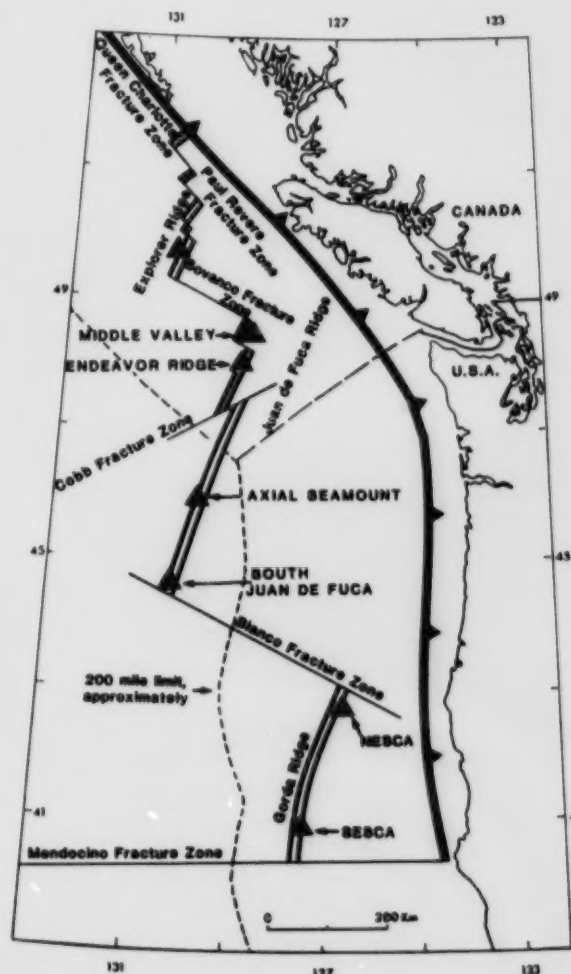


Figure 61.3. Location of sulphide deposits associated with active spreading ridges off the west coast of North America.



Figure 61.4. Side-lit bathymetric map of Explorer Ridge showing location of sulphide mounds in prominent central graben (after Geological Survey of Canada 1987b).



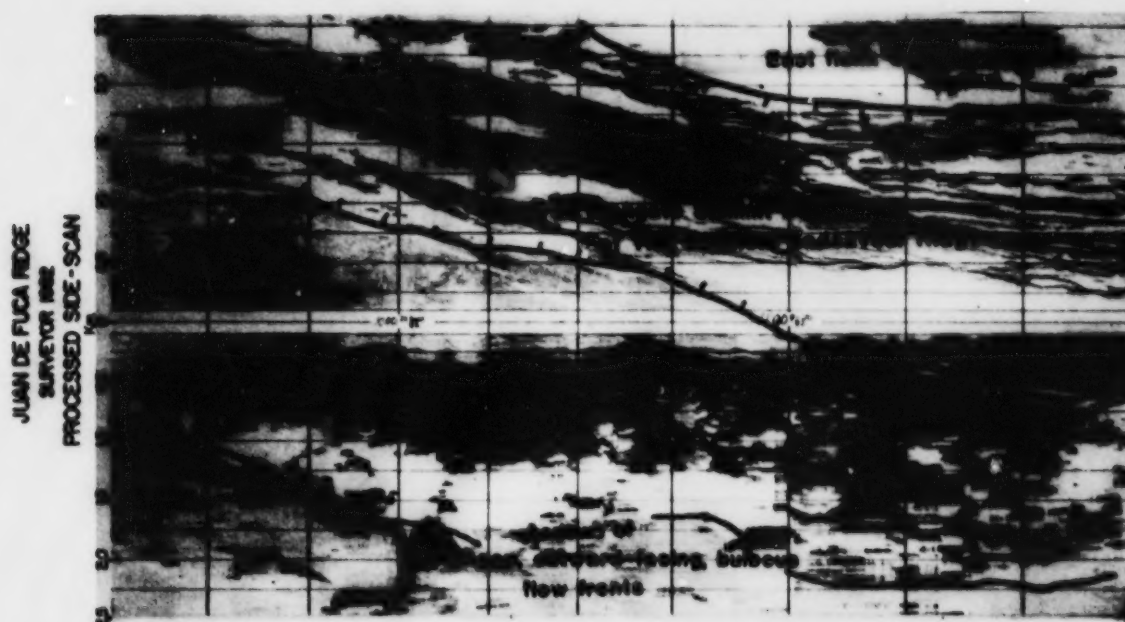


Figure 61.5. Side scan sonar image of Endeavor Ridge illustrating volcanic geomorphology.

tonic zone. The seismic cross-section in Plate 61.2 indicates that the highly sheared rocks of the Grenville Front tectonic zone can be traced as southeast dipping reflectors from the surface, where they are exposed, to mid- and lower crustal levels, where they originated (Green *et al.* 1987).

An enhanced understanding of the tectonic evolution of the Precambrian continental crust will facilitate mineral exploration in the Canadian Shield, just as elucidation of plate tectonic processes and of the history of accretion of far-travelled "foreign" terranes has contributed to the understanding of the formation and distribution of mineral deposits in the Cordillera. Although we can examine and explore many parts of Canada and its mineral deposits at the surface of the Earth, it is essential to extend this knowledge into the third dimension — depth. To accomplish this on a reconnaissance scale, we need to use integrated geological and geophysical "remote-sensing" technology to probe beneath the Earth's surface and this is best accomplished within co-operative projects such as GLIMPCE or LITHOPROBE. We will return to this subject below because projects such as these have been viewed skeptically by some observers as "academic" exercises that lack practical benefits; on the contrary, we are convinced that a better understanding of the nature and tectonic evolution of the continental crust in Canada is fundamental to the development of the metallogenic concepts that will guide the exploration for Canada's mineral and mineral fuel supplies for the future.

#### MINERAL DEPOSITS RESEARCH

Mineral exploration programs are usually based on a combination of regional geological knowledge with one or more mineral deposit models. One of the principal current thrusts of mineral deposits research at the GSC is the development of improved deposit models. A recent initiative in this area was the publication of a synopsis of the geological characteristics of 41 mineral deposit types important in Canada (e.g. Eckstrand 1984). The cornerstone of mineral deposit modeling is the availability of reliable descriptive data for individual mineral deposits on the regional as well as the local scale (Figure 61.6). Such data are often collected in the framework of an existing model, but the scientist must make certain that the preferred model does not preclude consideration of other possible models.

The descriptive mineral deposit model derives from the documentation of the various geological, geochemical, and geophysical attributes of individual mineral deposits. A model may be based upon a single deposit, but is more commonly a simplified representation of those characteristics considered to be the critical common elements of a number of deposits. An example of a well-documented descriptive deposit model is that for komatiite-hosted nickel sulphide deposits which are important in Archean greenstone terranes in Canada, Australia, and Zimbabwe. Figure 61.7 is a cross-section of Lunnion Shoot, a typical deposit of this type. Some components of the descriptive model for such deposits are illustrated in Figure 61.8, including the association

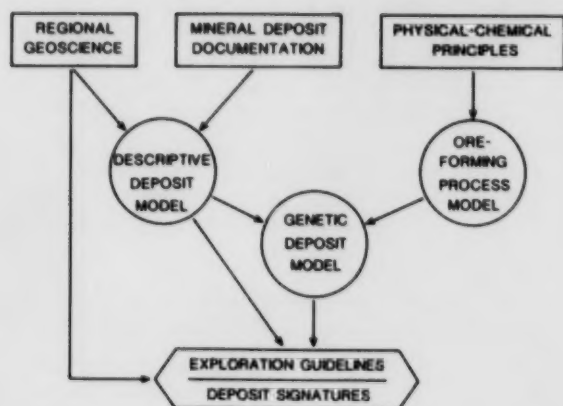


Figure 61.6. The relationship among different kinds of mineral deposit models and exploration.

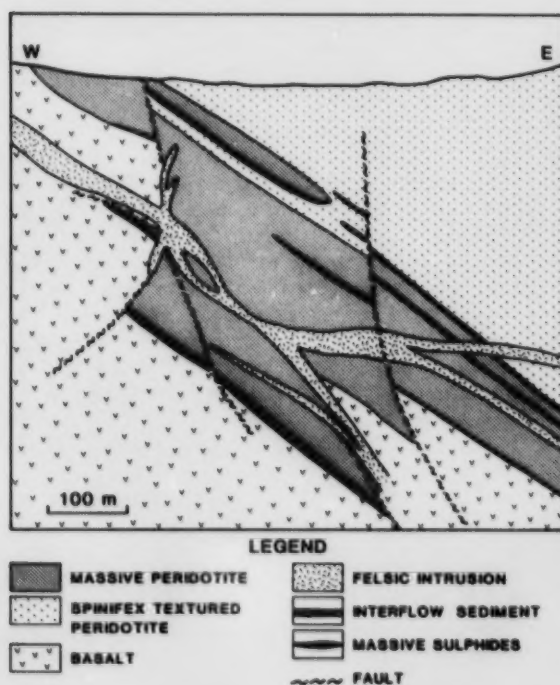


Figure 61.7. Cross-section of the Lunnon Shoot, a komatiite-hosted nickel sulphide deposit in Western Australia (after Ross and Hopkins 1975).

of the ores with thick, massive MgO-rich units at the base of the komatiite sequence, and the trend of decreasing MgO content upward through the succession of flows.

An integral part of the descriptive model is the array of geological, geochemical, and geophysical signatures which characterize the class of deposits. For example, the signatures of komatiite-hosted

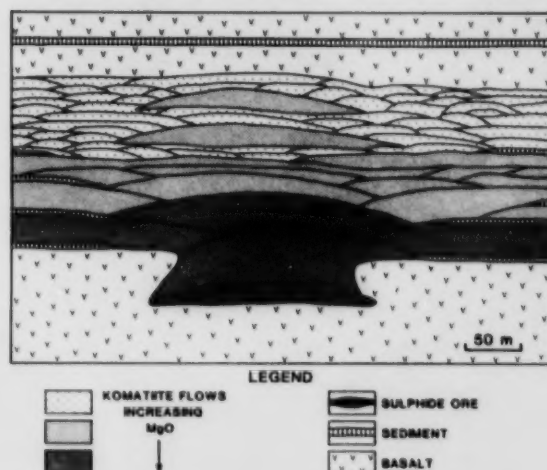


Figure 61.8. Some elements of the descriptive model for komatiite-hosted nickel sulphide deposits (after Lesher et al. 1981).

nickel sulphide deposits include the electrical, magnetic, and gravitational characteristics of the ore-bodies themselves, the compositional trends in the hanging wall rocks and, in some cases, geochemical dispersion of ore and pathfinder elements in the surficial environment.

While the descriptive model serves as a standard for comparison and is often a principal exploration tool, compilation of descriptive attributes without due consideration of genesis may result in spurious exploration guidelines. Consequently, an important objective of mineral deposits research is the formulation of genetic models. For example, komatiite-hosted nickel deposits are now generally believed to be magmatic sulphide accumulations that are syngenetic with their volcanic host rocks. Accordingly, the later faulting and felsic intrusions characteristic of many deposits (Figure 61.7) are excluded from the descriptive model (Figure 61.8). The genetic model not only allows refinement of the descriptive model, but may provide exploration guidelines in its own right. Volcanogenic massive sulphide, paleo-placer uranium-gold, and unconformity-associated uranium are but three examples of genetic models which have profoundly influenced exploration.

Genetic models may be either qualitative or quantitative, but in either case require an understanding of the physics and chemistry of ore-forming processes. As noted by Barton (1986), several different process models may apply to one deposit type. For example, a quantitative genetic model for porphyry copper deposits would incorporate equations describing the solubility of metals in aqueous fluids, the thermal regimes of a cooling pluton, and the flow of hydrothermal fluids through rocks,

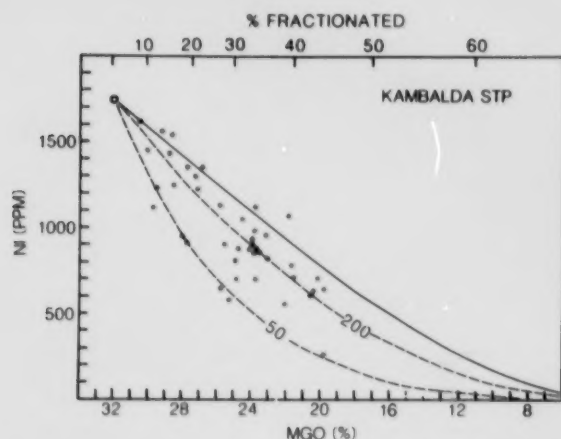


Figure 61.9. The variation of Ni and MgO in komatiite magma due to fractional crystallization of olivine from a sulphide-undersaturated magma (solid line), and fractional segregation of olivine and sulphide from sulphide-saturated magma in 200:1 and 50:1 ratios (dashed lines), calculated using the magmatic segregation process model of Duke (1979). The compositions of natural spinifex-textured komatiites from Kambalda, Western Australia (circles - data from Lesher et al. 1981) define a sulphide-saturated trend.

among others. Thus, ore-forming process models form the building blocks of genetic models.

Computer technology is allowing process modeling to become much more quantitative and much more predictive. For example, Figure 61.9 illustrates the compositional trends resulting from fractional crystallization of sulphide-saturated and undersaturated komatiitic magma (Duke 1979). The relative depletion in nickel in sulphide-saturated magmas predicted by the process model constitutes a signature of ore-bearing environments. The fact that the observed compositions of komatiites from the ore-bearing succession at Kambalda are depleted in nickel supports the use of the model as an exploration tool (Naldrett et al. 1984).

## EXPLORATION TECHNOLOGY

The GSC has made important contributions to the development of exploration technology over the years. Examples of geophysical methods include the airborne magnetic gradiometer system (Sawatzky and Hood 1975), as well as the airborne multi-element radiometric surveying technology described above. The GSC has also pioneered in some exciting areas of geochemical exploration. One of these involves the correction of stream silt sediment data to take account of the fact that different streams drain areas of different bedrock geology and therefore, require different background corrections (Bonham-Carter and Goodfellow 1985). This is illustrated by

the survey of the Cobequid Highlands of Nova Scotia in Plate 61.3. Contrast the large area of anomalous zinc values indicated by the raw data with the much more focused residual anomalies after the data have been filtered using catchment basin analysis.

The integrated application of different mineral exploration technologies promises to be the hallmark of future successes in mineral exploration. Pattern recognition, based on the application of image analysis technology to the integration of geological, geochemical, and geophysical data sets with satellite imagery, provides one interesting example.

Recent work by the Geological Survey of Canada on the world class tungsten deposits, which occur in the Canadian Cordillera near the boundary between the Yukon and Northwest Territories, are a case in point (Aronoff et al. 1986). The tungsten deposits are difficult to detect if not exposed by erosion. They formed in sedimentary rocks overlying granitic intrusions. The genetic model for these deposits (Plate 61.4) predicts that ring fractures will develop in the roof rocks during intrusion of the granite, which in turn controls the formation of the orebodies. The ring fractures subsequently control the circulation of groundwaters through the deposits and the discharge of anomalous concentrations of tungsten, copper, and other ore metals into surface streams, where they may be detected as geochemical anomalies in analyses of surface water samples. Enhanced digital satellite imagery aids in the recognition of the characteristic ring fractures, and computer-based image analysis technology makes possible the superposition of geological and geochemical data on the satellite image, to show the spatial relationships among granitic plutons, anomalous tungsten levels in stream waters, and the ring fractures associated with the Lened tungsten deposits (Plate 61.5). Another geochemical anomaly occurs to the southeast of the Lened deposits. Although no granitic body has been observed there, the computer-enhanced satellite image indicates the presence of a ring fracture, suggesting that a granitic intrusion occurs not far below the surface, and that this too is a promising target for tungsten exploration.

## NEW FRONTIERS AND NEW CHALLENGES

Government geoscience is moving into new frontiers that involve new challenges requiring new technologies and new strategies. The Geological Survey of Canada has made major commitments on two new frontiers: the deep geology of the continental crust, and the seabed in Canada's offshore areas. We have adopted the same strategy in both areas — a coordinated, multidisciplinary, problem-oriented, team approach, involving close collaboration with geoscientists from the universities, provincial agencies, and industry. The most conspicuous example is



LITHOPROBE, a multidisciplinary project with major financial support from both the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Geological Survey of Canada, which literally aims to probe the lithosphere to extend geological knowledge of Canada into the third dimension. This joint venture is an example of "big science". It operates under a Board of Directors representing the Canadian university community, the GSC, and industry, and has already conducted successful experiments in the southern Canadian Cordillera, the Atlantic continental shelf, and the Great Lakes area. For 1987, the main focus of effort was the Kapuskasing Structural Zone, a north-south-trending fault structure that transects the Abitibi greenstone belt, and offers the prospect of elucidating the deep roots of the Archean greenstone belt that hosts many of the most important gold and base-metal deposits in Canada. Although the short-term benefits of this type of "big science" project may not be readily apparent, we do think there are very important practical benefits for mineral exploration.

Deep crustal studies will benefit mineral exploration through elucidation of the relationships among geological age, mineral deposit formation, and tectonic processes. The crust can be divided generally into parts that are tectonically active and those that are tectonically dormant. Our understanding of the various crustal components comes largely from knowledge of crustal mechanisms that operate in its tectonically active and geologically younger parts such as, for example, offshore spreading ridge zones and subduction processes at the leading edge of continental plates. The relationships between tectonics and the distribution of mineral deposits in these areas are becoming well understood: however, 10 or 15 years ago we could not even attempt to show such relationships.

It was only in the late 1970s that the first observations of "Black Smokers" and the formation of spreading-ridge vent-associated sulphide accumulations on the seafloor were made. It was only in the early 1980s that the significance of this phenomenon, its widespread occurrence, and its probable replication in older "fossilized" land terranes began to be appreciated. Now, with the coupling of these observations on the seafloor and the increased understanding of the processes and products of global tectonics, we begin to see that mineral deposits of certain types and certain geological associations occur where they do (geologically and geographically) not by accident, but because they are related to the tectonic processes that established their environments. We understand the tectonic processes of the modern seafloor fairly well. We understand the tectonic architecture of the continental margins (Cordilleran and Appalachian Regions) less certainly, but we can deduce the general principles and mechanisms. We begin to see how the environments of

mineral deposits fit into these tectonic mosaics, in general terms, although we have many details yet to unravel. When we get back into the Precambrian, however, our landmarks are much less certain and there is much work to do. We have clues, scattered benchmarks along the way, but the picture is still very murky. Our current detailed knowledge of the interior of the continent is generally limited to its surface skin. However, through deep seismic soundings and other indirect interpretive techniques, we are beginning to build a better picture. One of the most exciting challenges in earth sciences in the future will surely be to unravel the tectonic architecture and processes of the Precambrian. In doing so, if the present is truly the key to the past, we should undoubtedly gain a vastly improved understanding of the processes of mineral deposit formation in these ancient tectonic regimes. In this sense, we are looking for the "tectonic signatures" of mineral deposits which will be critical for exploration in the future.

## ACKNOWLEDGMENTS

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## 62. Integrated Geophysical and Geochemical Exploration in China

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### ABSTRACT

Over the last decade, geophysical and geochemical exploration has been widely used by the Ministry of Geology and Mineral Resources (MGMR) in various fields of geological investigation. To date, about 87 percent of China's territory has been covered by airborne magnetic surveys, 62 percent by regional gravity, and 19 percent by regional geochemistry. Meanwhile, a great volume of geophysical and geochemical exploration has been completed for mineral resources, groundwater, and geothermal energy, and abundant geological results of prospecting have been obtained. At present, mineral prospecting is being intensified. The ministry has started on a new round of geophysical and geochemical prospecting for solid mineral resources, aiming at searching for deep-seated, hard-to-recognize, and new types of ore deposits and those occurring in areas of difficult access. For this purpose, the following technical measures have been or will be taken, namely:

1. The improvement of the accuracy of geophysical observations and the detection limits of analytical methods for geochemical samples.
2. The development of borehole and other geophysical and geochemical methods of exploration with greater penetration.
3. The application of integrated geophysical methods for indirect ore exploration and establishment of geological-geophysical-geochemical models for various types of deposits to guide the prospecting.
4. The application of a reasonable integration of methods to form an optimal procedure of prospecting.

### INTRODUCTION

The work of exploration in the future is a problem of common concern, and earth scientists of all countries are challenged to solve a series of exploration problems. The MGMR of China has completed a great deal of geophysical and geochemical investigation throughout the country. From now on, the scope of geophysical and geochemical prospecting will be expanded and more difficulties will appear. This requires us to consider seriously the future plan of prospecting and technical measures to deal with the situation.

### REGIONAL GEOPHYSICAL AND GEOCHEMICAL SURVEYS

Airborne magnetic surveys have been conducted in China for many years. Figure 62.1 shows their coverage, which accounts for 87 percent of the territory of our country, as well as 1 200 000 km² of the adjacent sea area. These surveys have mainly been completed using airborne nuclear precession magnetometers and fluxgate magnetometers, at a scale of 1:50 000–1:1 000 000. Now an aeromagnetic map at a scale of 1:1 000 000 east of 102°E and has been compiled and published. In addition, airborne EM and  $\gamma$ -ray spectrometric surveys have been conducted in some metallogenic regions (Zho 1987).

A nation-wide regional gravity survey at a scale of 1:100 000–1:1 000 000 has been under way systematically, covering 62 percent of the whole territory of China, as shown in Figure 62.2, which includes the gravity measurement by the Ministry of the Petroleum Industry and the Ministry of the Coal Industry. A gravity-base network of the first order and 23 calibration stations have been established in 25 provinces. In order to meet the requirements of map compilation, we have defined a series of techni-

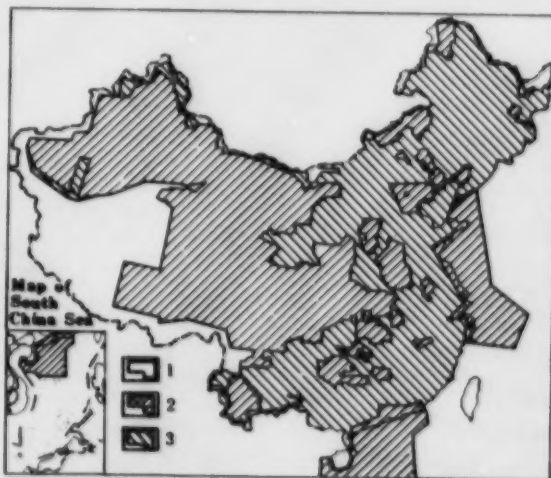


Figure 62.1. Schematic map showing coverage of aeromagnetic survey in China. Legend: 1. area uncovered yet by aeromagnetic survey; 2. area covered by aeromagnetic survey using nuclear precession magnetometer; 3. area covered by aeromagnetic survey using fluxgate magnetometer.

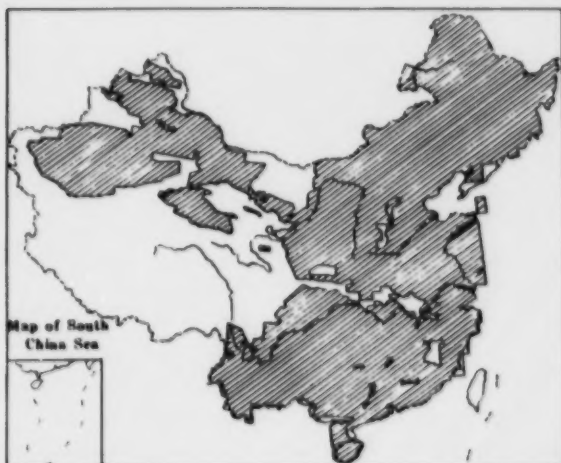


Figure 62.2. Schematic map showing coverage of regional gravity survey in China.

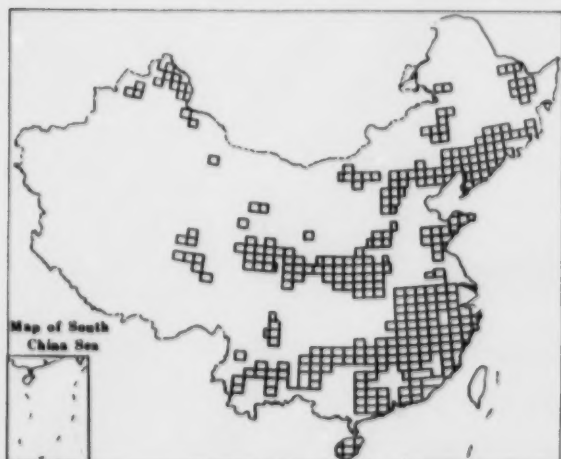


Figure 62.3. Schematic map showing coverage of regional geochemical survey in China.

cal specifications, which include a unified gravity system, unified plane co-ordinate system and elevation system, unified normal gravity formula and altitude correction formula, unified density of intermediate layer ( $2.67 \text{ g/cm}^3$ ), and unified radius for topographic correction ( $166.7 \text{ km}$ ). The existing gravity data have also been recalculated according to the technical specifications mentioned above. A national gravity map is now being compiled (Sun and Zuo 1986).

A nationwide project of regional geochemical surveys is now underway. The coverage, shown in Figure 62.3, accounts for 19 percent of our territory. Because China is a mountainous country with well-developed drainage systems, we use the stream sedi-

ment survey as the main method, with a sampling density of  $1 \text{ sample/km}^2$ . Samples from each  $4 \text{ km}^2$  unit will be mixed to make a composite one, from which 39 elements are analyzed quantitatively. Also, geochemical standard reference samples have been prepared and a data-monitoring system developed. In regions with special landscapes, effective geochemical methods and reasonable sampling density are selected through an experimental investigation (Xie 1979; Rong and Sheng 1986).

A geophysical study of the deep crustal structure has been done on the Qinhai-Tibet plateau, and in Panxi and other areas. Seismic soundings have been carried out on profiles with a total length of  $6630 \text{ km}$  by MGMR. For several segments of these profiles, magnetotelluric soundings, geomagnetic variation method, and geothermal flow measurement have been used in combination.

As a result, the study of the characteristics of the geophysical field over a large area and of the geographical distribution of various elements in natural surface materials provides not only the basis for solving a number of fundamental geological problems, but also provides abundant prospecting information for reducing the target area more rapidly. For example, by the end of 1985, following up the airborne-magnetic anomalies on the ground, 449 metallic and nonmetallic deposits and prospects had been discovered or expanded. Among them, 132 were of large and medium sizes (Zho 1987).

Obviously, regional geophysical and geochemical surveys are a kind of basic geological investigation of strategic significance. We shall continue to attach importance to them in the future. The regional gravity and geochemical surveys will be speeded up in the workable areas of our country. At the same time, a second-generation airborne geophysical survey will be carried out, in which the accuracy of airborne-magnetic survey will be improved; the integrated aeromagnetic, airborne  $\gamma$ -ray spectrometric and airborne EM methods will be applied; and the measuring techniques will be improved. Meanwhile, several profiles of deep geophysical investigation will be conducted across the country.

### A NEW ROUND OF GEOPHYSICAL AND GEOCHEMICAL PROSPECTING FOR SOLID MINERAL RESOURCES

The MGMR has carried out geophysical and geochemical exploration for nearly 60 types of minerals over the whole country (except Taiwan Province). In prospecting for a variety of generic types of magnetite, the magnetic method gives the best result. Most of the known magnetite deposits in our country have been discovered or expanded on the basis of geophysical data and some of them have already become important iron mines in China. Integrated geophysical and geochemical methods have been used successfully to discover a number of base

metallic and rare metallic ore deposits. Positive results have also been obtained in the geophysical exploration of some nonmetallic deposits. With the breakthrough in analytical techniques in recent years, great progress has been made in geochemical prospecting for gold. For example, through geologic evaluation and engineering confirmation from 1981 to 1985, 443 mineral deposits and prospects were discovered or expanded in the potential areas located on the basis of geophysical and geochemical data. Among them were 119 deposits of large to medium size (Zou 1985).

At present, mineral prospecting is becoming increasingly difficult, and we are assigned to search for deep-seated, hard-to-recognize new types of ore deposits and those occurring in areas difficult to access. For this purpose, we are launching out into a new round of geophysical and geochemical prospecting for solid mineral resources, with the emphasis laid on the important metallogenic zones of our country. The technical measures which have been or will be taken are outlined below.

#### THE IMPROVEMENT OF THE ACCURACY OF GEOPHYSICAL OBSERVATION AND OF THE DETECTION LIMITS OF ANALYTICAL METHODS FOR GEOCHEMICAL SAMPLING TO IMPROVE THE DETECTION ABILITY OF PROSPECTING

The effectiveness of geochemical prospecting depends largely upon the detection limits of analytical methods. Table 62.1 gives the detection limits for element analysis of geochemical samples at different periods. The semiquantitative spectrographic method was used mainly before 1980, so that the

detection limits of over half of those 39 elements listed in Table 62.1 could not meet the requirements of geochemical exploration. Therefore, on the previous geochemical maps, only the anomalies of Cu, Pb, Cr, Ni, Sn, and others could be shown, with the anomalies of W and Ag indicated sporadically, while the anomalies of Hg, Sb, U, Au, and other elements were difficult to locate. In recent regional geochemical surveys, the detection limits of element analysis have already met the requirements listed in Table 62.1, so that the content of most of the listed elements can be reported for 90 percent or more of the samples.

For example, the application of geochemical exploration for gold was very limited, because the detection limit for gold was only 1 to 2 ppm in the 1950s and 1960s. By the fall of 1979, a spectrochemical method for trace gold analysis was developed successfully. The detection limit of gold reached a new level of 0.5 to 0.3 ppb, making it possible for gold to be a direct indicator-element in gold prospecting, and thus raising the effectiveness of geochemical prospecting for gold.

It can be seen from the gold anomaly map of a certain area in the Ke You Zhong County, Inner Mongolia, that when the detection limit of gold was set at 1 ppm, only a few individual points of high gold content were observed (Figure 62.4b). But with a detection limit of 0.3 ppb, distinct gold anomalies were located (Figure 62.4a). From 1981 to 1985, 108 gold deposits and prospects were discovered by the above-mentioned geochemical exploration method, among them 14 were of large to medium size.

TABLE 62.1. CONTRAST BETWEEN REQUIREMENTS FOR DETECTION LIMITS OF ELEMENTS IN GEOCHEMICAL SAMPLES IN DIFFERENT PERIODS (from Li Shanfang, Sun Huanzhen).

Element	Detection Limit (in ppm)			Element	Detection Limit (in ppm)		
	Before 1960	From 1960 to 1979	After 1980		Before 1960	From 1960 to 1979	After 1980
Ag	1	0.1	0.02	Mo	5	0.5	0.5
As	100-200	50	1	Nb	100	20	5
Au			0.0003	Ni	10	3	1-10
B	10	5	5-10	P	1000	400	100
Ba			50	Pb	10	2.5	1-10
Be	2.5		0.5	Sb	200	50	0.2
Bi	10	5	0.1	Sn	10	2.5	1-3
Cd	50	10	0.1	Sr			5-50
Co	10	2.5	1	Ti		10	100
Cr	20	5	15	Th			4
Cu	1	1	1	U			0.2-1
F			100	V	10	2	20
Fe			1000	W	100	50	0.5
Hg		0.03	0.01	Y	500	100	5-10
La			30	Zn	100	10	10
Li			5	Zr	200	50	10
Mn		50	30				



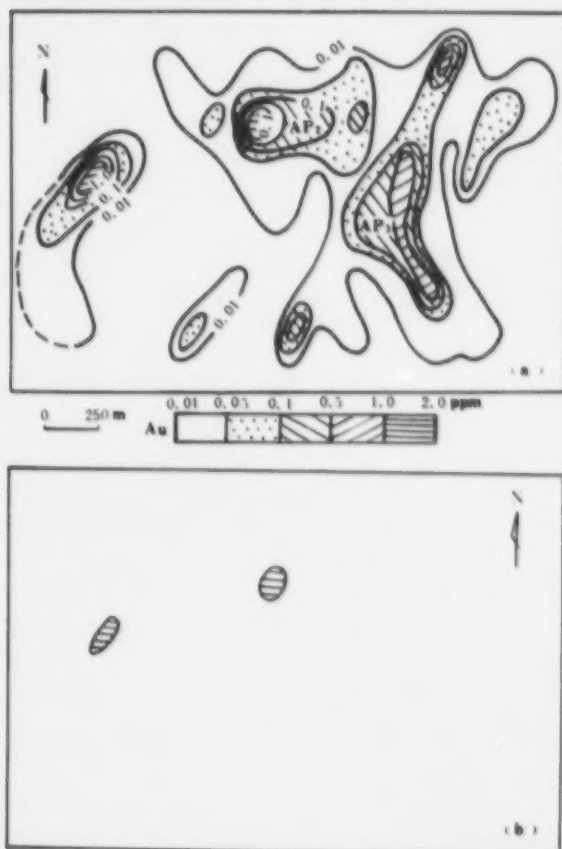


Figure 62.4. Gold anomalies in a certain area of Ke You Zhong County, Inner Mongolia (from Sun and Zheng 1987).

The geochemical exploration method is the most effective, especially for the fine-disseminated type of gold deposits, which are hard-to-recognize macroscopically or even under a microscope. For example, there was a small-sized deposit of arsenic in southwestern Guizhou Province. As a result of the 1:10 000 scale soil geochemical survey, five gold anomalies were located, as shown in Figure 62.5. But the gold content of their inner zones was just a little over 0.3 ppm. In Figure 62.6, after the engineering examination of the three anomalies Au1, Au2, Au3, gold mineralization zones were revealed and commercial orebodies with a thickness of more than 10 m were located. These gold deposits belong to the fine disseminated type and mainly occur in clay rocks and sandstones of the Triassic age (Sun and Zheng 1979; Chen 1985).

The effectiveness of geophysical prospecting also depends upon its observation accuracy. In recent years, the high-accuracy airborne magnetic survey conducted in our country, which can detect weak anomalies of only several nT, has made it possible

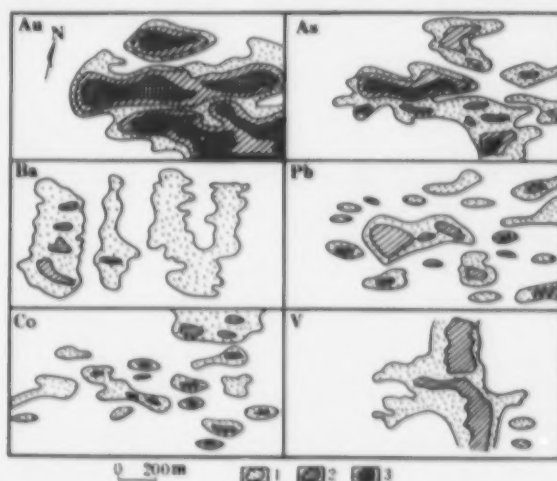


Figure 62.5. Geochemical anomalies in a certain gold ore deposit of southwestern Guizhou Province (from Chen 1985). In legend, Pattern 1 values for elements are given in ppm as follows: Au 0.075-0.15, As 300-600, Ba 600-850, Pb 20-30, Co 20-33, and V 300-400. Pattern 2 values are given in ppm as follows: Au 0.15-0.3, As 600-1000, Ba >850, Pb >30, Co >33, V >480. Pattern 3 values for elements are given in ppm as follows: Au >0.3, As >1000.

for us to look for strongly magnetic bodies buried at great depths and to detect the distribution of poorly magnetic bodies.

For example, it can be seen from Table 62.2 that a 1:1 000 000 scale airborne magnetic survey in a weakly magnetized area in central Guizhou Province was completed in 1959, and because of the technical limitation at that time, especially the lack of accurate topographic maps for navigating the aircraft, the total accuracy was as low as  $\pm 0.56$  nT.

Figure 62.7 shows the great difference between the two. On the contour map (A) produced in 1959, only a "quiet" magnetic field is indicated, while on (B), that of 1985, some low and regular anomalies with an intensity of 6 to 18 nT are observed. They are interpreted as the reflection of structures of poorly magnetized basement, thereby providing valuable data for the study of tectonic structures in the whole region (Jin *et al.* 1986).

In order to improve the total accuracy of aeromagnetic survey up to 1 to 5 nT, in addition to the application of homemade optically pumping aeromagnetometer with a sensitivity up to  $\pm 0.1$  to  $\pm 0.02$  nT, many important improvements have been made in navigation and location, altimetry, magnetic compensation, data acquisition, and correction techniques (Zho 1987). At the same time, the total accuracy of the ground magnetic method has been correspondingly raised to 2 to 3 nT.

A model of a gravimeter with a thermostat is produced in our country. Its dynamic accuracy of

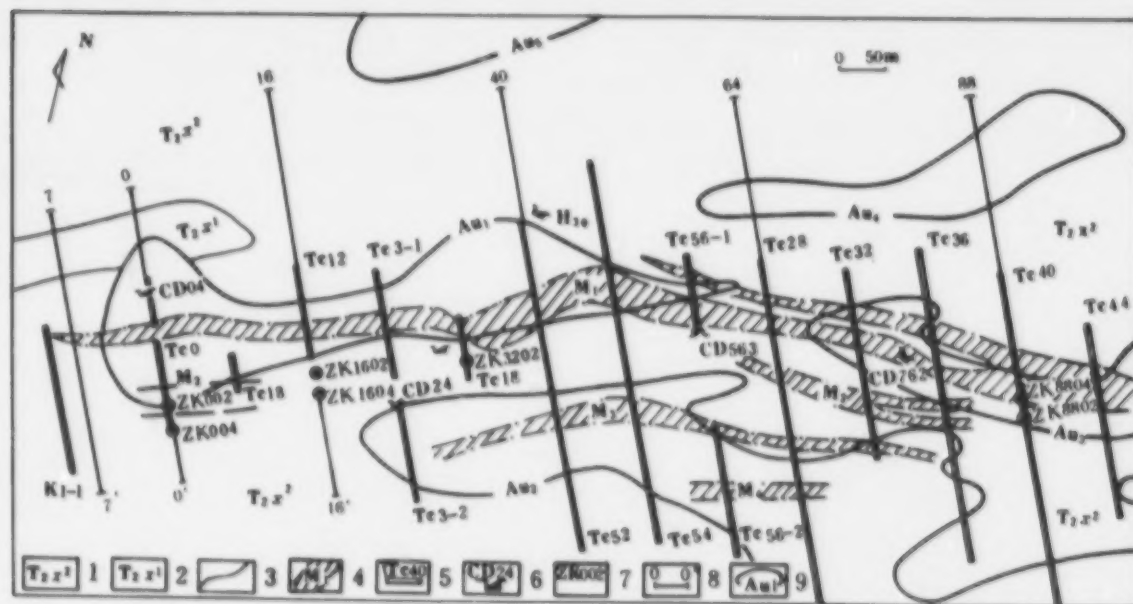


Figure 62.6. Diagram showing the engineering examination of the anomalies in a certain gold ore deposit of southwestern Guizhou Province (from Chen 1985). Legend: 1. claystone and sandstone of Middle Triassic Xinyuan Formation; 2. micrite of Middle Triassic Xinyuan Formation; 3. geological boundary; 4. gold ore belt and its serial number; 5. exploratory trench and its serial number; 6. adit and its serial number; 7. drillhole and its serial number; 8. exploration line and its serial number; 9. gold anomaly and its serial number.

TABLE 62.2. CONTRAST BETWEEN RESULTS OF AEROMAGNETIC SURVEY AT DIFFERENT PRECISIONS IN CENTRAL GUIZHOU PROVINCE (from Jin *et al.* 1986).

Year of Survey	Scale of Survey	Instrument Employed	Sensitivity of Instrument	Precision of Survey	Scale for Map	Map Compilation Longitudinal	Contour Interval
In 1959	1:1 000 000	A3M - 49 Type flux - gate magnetometer	5 nT	$\pm 12.5$ nT	1:1 000 000	1 cm = 200 nT	25 nT
In 1985	1:400 000	GQ - B Type optical pumping magnetometer	0.1 nT	$\pm 0.56$ nT	1:200 000	1 cm = 2 nT	0.5 nT

observation has already been raised to 0.03 mg/l. Improvements have been made in geodetic measuring techniques and topographic corrections, which enables us to do more extensive high-accuracy gravity prospecting.

#### THE DEVELOPMENT OF BOREHOLE AND OTHER GEOPHYSICAL AND GEOCHEMICAL METHODS WITH GREATER DEPTH PENETRATION

The application of borehole and other geophysical and geochemical methods is of great significance in making full use of boreholes to detect deep-seated blind orebodies at the bottom of, between, or near the boreholes. The application of borehole three-

component magnetometry in the Matoushan cupreous magnetite deposit, Anhui Province, is a successful case history. In the late 1970s, more than 10 boreholes were drilled to a depth of 500 m at the central part of the magnetic anomaly of this area, but failed to intersect ore in any of them (Figure 62.8). In 1983, another deep borehole ZK0341 (902 m deep) was drilled on the northwest side of the anomaly, with only diorites and skarn found.

In order to reveal the nature of the magnetic anomaly, borehole three-component magnetometry was carried out and a distinct anomaly was located at the interval from 400 to 800 m as shown in Figure 62.9. As a result of interpretation, a blind orebody was expected in the southeast side of this borehole.

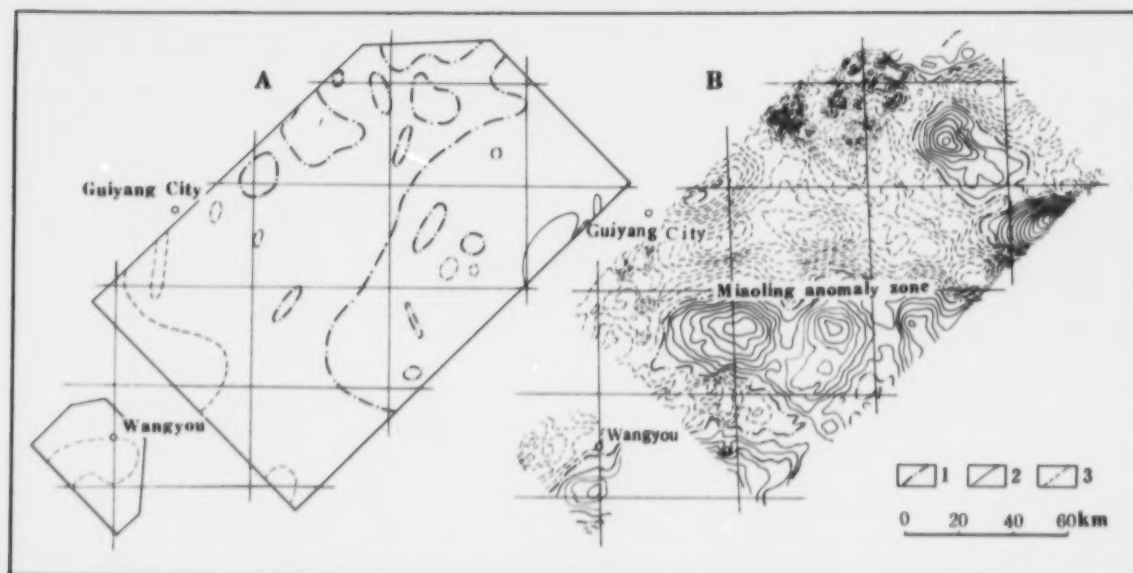


**Figure 62.7.** Contrasting results of aeromagnetic survey of different accuracy in central Guizhou Province (from Jin et al. 1986). A. contour map of  $\Delta T$  by using a 3M-49 type fluxgate magnetometer (5 nT) in 1959 (1:1 000 000, contour interval being 5 nT). B. Contour map of  $\Delta T$  by using optically pumped magnetometer (0.1 nT) in 1985 (1:400 000, with contour interval being 1 nT, and being 0.5 nT in original map). Legend: 1. zero contour line of  $\Delta T$ ; 2. positive contour line of  $\Delta T$ ; 3. negative contour line of  $\Delta T$ .

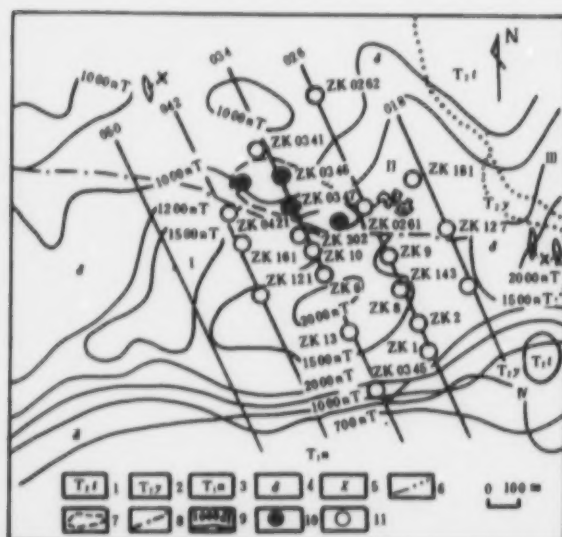


**Figure 62.8.** Diagrammatic geological-geophysical map of Matoushan copper ore deposit, Anhui Province (from Rong and Sheng 1986). Legend: 1. Middle Triassic Tongtouljian Formation; 2. Middle Triassic Yueshan Formation; 3. Lower Triassic Nanlinghu Formation; 4. diorite; 5. lamprophyre; 6. measured and inferred geological boundaries; 7. boundary of inferred magnetic orebody; 8. front projection of inferred marble body; 9. contour line of  $\Delta\sigma$ ; 10. drillhole intersecting orebody; 11. drillhole not intersecting orebody.

Finally, a 97 m thick cupreous magnetite body was discovered by drilling at the interval 481.87 to 578.9 m in borehole ZK0342. The orebody occurs at the contact between the Triassic formation and diorites. Several subsequent boreholes also have made discoveries, respectively (Figure 62.9).

Another good example is the Xiangzikou cupreous pyrite deposit in Hubei Province. The exploration work for this deposit ended in 1966, primary halo geochemistry was started in 1977. The primary dispersion halo of copper at the pinch-out end of the orebody was discovered to expand remarkably, and the content of copper tended to increase. It was inferred that there was a blind orebody at depth. Two boreholes, CK1002 and CK1003, drilled afterwards, all encountered ores. For example, the accumulative thickness of the orebody discovered in CK1002 reaches 80 m and more (Figure 62.10). In addition, the boreholes drilled along the adjacent profiles also made industrial discoveries, thus considerably increasing the reserves of Cu and S in this area (Zhou and Wang 1981).

Furthermore, good results have also been obtained in the application of the borehole electromagnetic wave method and borehole IP method to exploration for some chromite and base-metal ores. At present, the development of a miniaturized integrated borehole geophysical system, with its sensitivity improved, is well underway.

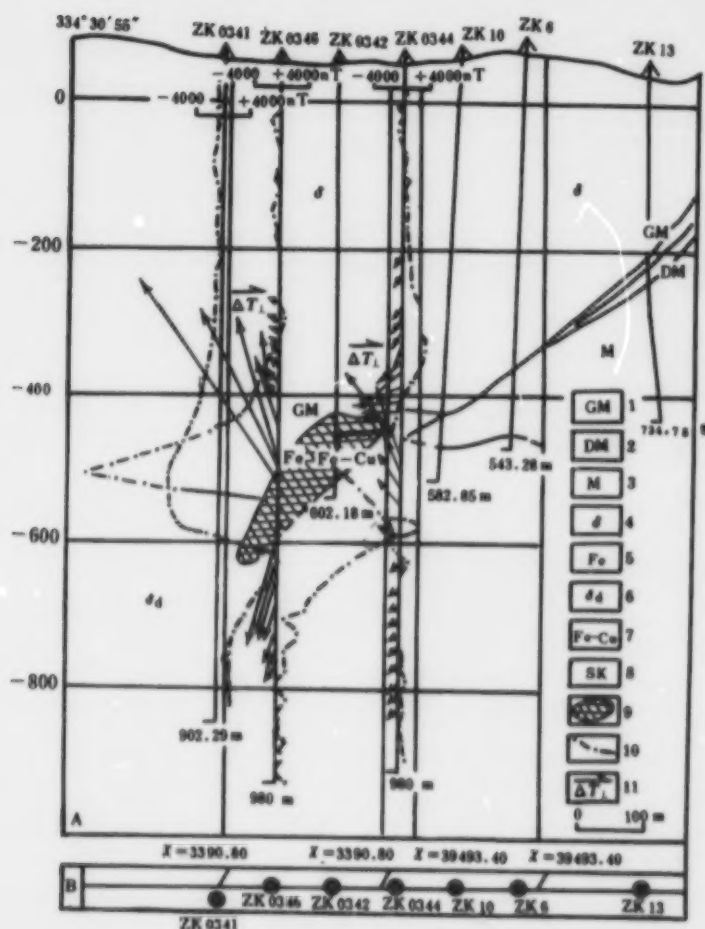


Figure 62.9. Profile of borehole magnetic survey along Line No. 034 of the Matoushan copper ore deposit, Anhui Province (from Rong and Sheng 1986). Legend: 1. brecciated marble; 2. dolomitic marble; 3. marble; 4. diorite; 5. magnetite; 6. diopside diorite; 7. cupreous magnetite; 8. skarn; 9. orebody 10. curves of borehole magnetic survey ( $\Delta Z$ ); 11. projection of general vector  $\Delta T_g$  on Line No. 034.

In order to search for deep-seated orebodies, some geophysical and geochemical methods with great penetration have been developed. Several models of medium- to high-powered resistivity and IP units for prospecting have been manufactured, in order to carry out prospecting with high power electric methods. The transient EM method and spectral IP methods have found their application in prospecting for conductive sulphide deposits buried at greater depths, wherever conditions permit. In order to do stereomapping in conjunction with geological investigations, electromagnetic frequency sounding has been developed to detect some ore-bearing layers and ore-controlling structures.

Soil mercury-vapour surveys have been conducted in prospecting for mercury-bearing sulphide deposits in areas covered by thick transported overburden.

#### THE APPLICATION OF INTEGRATED GEOPHYSICAL METHODS FOR INDIRECT ORE EXPLORATION AND ESTABLISHMENT OF GEOLOGICAL-GEOPHYSICAL-GEOCHEMICAL MODELS FOR VARIOUS TYPES OF DEPOSITS TO GUIDE PROSPECTING

It is well known that metallic and nonmetallic ore deposits are controlled by definite geological conditions both in genesis and in space. In most cases, geophysical methods may be useful for detection and elucidation of some ore-controlling geologic factors (such as intrusives, fracture zones, folds, volcanic mechanics, ore-bearing layers associated with some characteristic minerals, etc.) and association indicators of certain orebodies (such as wall rock alteration and mineralization zones) for indirect prospecting. Particular attention should be paid to indirect prospecting when there is no distinct physical con-



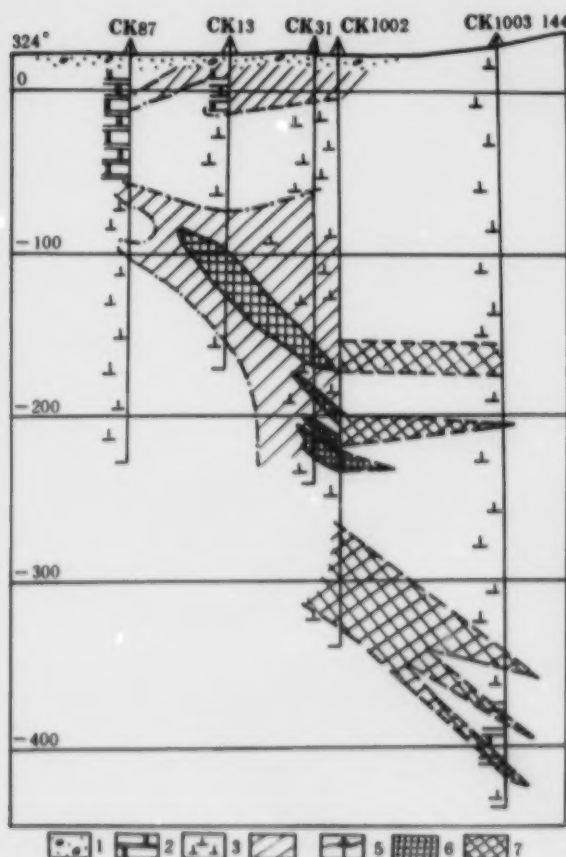


Figure 62.10. Profile of primary halos of copper along Line No. 10 of the Xiangzikou copper ore deposit in Hubei Province (from Yate and Jinhua 1981). Legend: 1. slope materials; 2. marble; 3. diorite; 4. primary halo of copper; 5. drillhole; 6. sulphide orebodies explored in 1966; 7. ore thickness detected through anomaly verification in 1977.

trast between rocks and ores, and the existing geophysical methods can hardly detect the "response" from orebodies themselves. In this way, we can expand the scope of geophysical prospecting.

The successful discoveries of some gold deposits of Zhaye district, Shandong Province, with the geophysical method is a good example in this respect. The gold bodies occur in the altered fracture zone between granites and metamorphic rocks of the Jiadong group and in the fracture zones within granites and metamorphic rocks. According to the data obtained from measurement of physical properties, the apparent resistivity ( $\rho_a$ ) of the granite (>1500  $\Omega m$ ) is higher than that of the metamorphic rock (<350  $\Omega m$ ), while that of the fractured rocks is remarkably reduced. Here, gold is associated with pyrite and other sulphide minerals, causing the polarizability ( $\eta_s$ ) of the ores to increase.

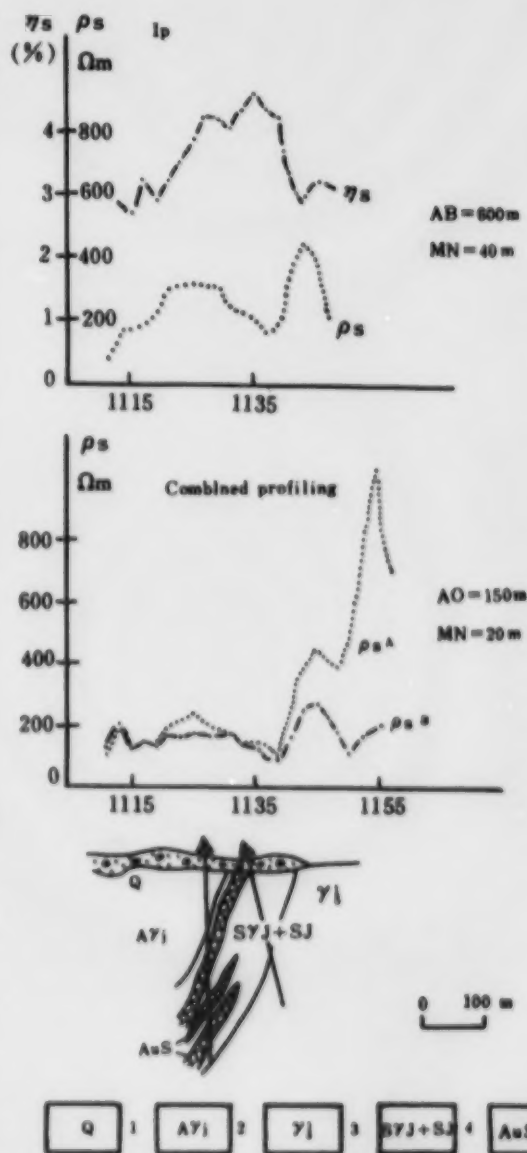


Figure 62.11. Comprehensive geological-geophysical profile of the Dongji gold ore deposit (from Xiao and Gu 1984). Legend: 1. Quaternary; 2. strata of Jiadong group; 3. Linglong granite body; 4. altered fracture zone; 5. gold orebody.

Therefore, Figure 62.11 shows that the altered fracture zone is indicated by curve  $\eta_s$  of combined profiling (resistivity profiling with combined pole-dipole array). Meanwhile, the IP anomaly successfully located the enriched zone of gold-bearing sulphides, and hence delineated the distribution of the gold orebody indirectly.

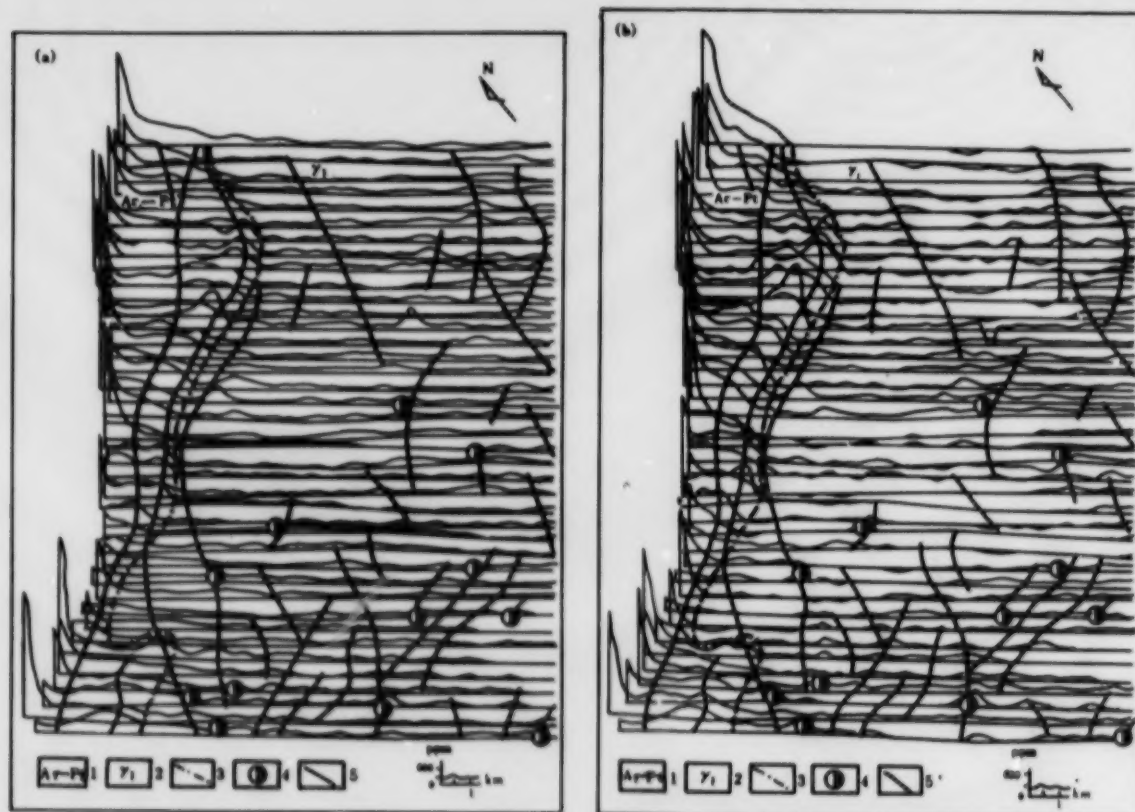


Figure 62.12. Map of real and imaginary components of dual-frequency airborne electromagnetic survey in Zhaoze District, Shandong Province. Figure 62.12a - AEM/HR Map. Figure 62.12b - AEM/Li Map. Legend: 1. metamorphic rock of Jiaodong group; 2. granite; 3. boundary between geological units; 4. site of known gold deposit; 5. fractured zone interpreted from airborne electromagnetic data.

A 1:50 000 scale dual-frequency airborne EM survey (463 and 1563 Hz) was conducted over the region, with IP survey and combined profiling carried out in some promising areas. As a result, both real (Figure 62.12a) and imaginary (Figure 62.12b) component curves give distinct anomalies over the altered fracture zones. A drastic change appears on both sides of the contact fracture zone due to a great contrast of electrical properties between granite and metamorphic rock. Based upon airborne EM anomalies, several tens of fracture zones have been interpreted, thus reducing the target area in prospecting for gold (Figure 62.12).

The IP survey succeeded in locating a number of well-defined anomalies, one of which is due to the Jiaojia gold deposit (Figure 62.13). The result of exploration indicated that the projection of the top of the gold body to the ground approximately coincides with the centre of the IP anomaly in position. Based upon the geophysical and geochemical data, a number of gold deposits have been discovered in this region (Xiao and Gu 1984; Zou 1984).

It is an inevitable trend of development to give full play to indirect prospecting, which requires an adequate knowledge of ore-controlling geologic conditions and other geophysical characteristics. Therefore, it is necessary to establish geological-geophysical-geochemical models for various types of deposits, based upon the comprehensive analysis for the data available on the known ore deposits. According to these models, the objectives of prospecting, the preferred combination of methods and techniques, as well as the principles of interpretation, may be well defined.

#### THE APPLICATION OF REASONABLE INTEGRATION OF METHODS AND TECHNIQUES TO FORM AN OPTIMAL PROCEDURE OF PROSPECTING

It is advisable to make a unified plan for the geological survey, remote sensing, geophysical, and geochemical investigations, etc., to be conducted in the same area, so that they can display their own merits and co-ordinate with each other. This will improve the effectiveness of prospecting with a re-

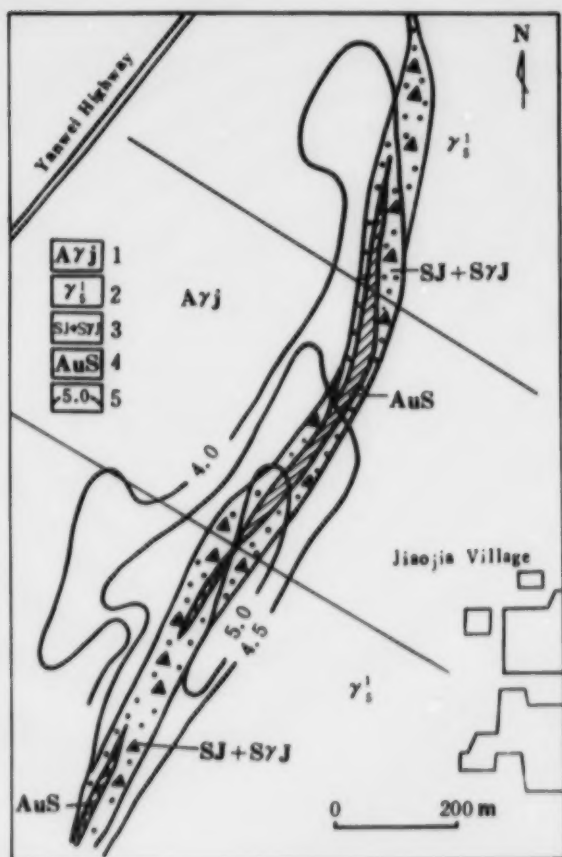


Figure 62.13. Comprehensive geological-geophysical map of the Jiaojia gold ore deposit in Zhaoye District, Shandong Province (from Xiao and Gu 1984). Legend: 1. strata of Jiaodong group; 2. Linglong granite; 3. altered fracture zone; 4. gold orebody; 5. contour line of  $\eta_s$ .

duction in both the time and cost of prospecting. It is therefore necessary to make a reasonable plan of exploration according to the actual conditions of different regions in order to establish an optimal procedure of prospecting.

Regional geophysical and geochemical work should be conducted in the important metallogenetic and promising zones. In areas which are poorly studied and lack systematic regional geophysical and geochemical data, the 1:200 000 scale regional geochemistry and regional gravity survey should be conducted first, in addition to a full utilization of the available aeromagnetic data. Based upon a comprehensive interpretation of the available data of regional geologic survey, remote sensing, and regional geophysics and geochemistry, large- to medium-scale metallogenetic prognosis will be carried out in order to select priority areas for prospecting. In areas of adverse physiographic conditions, the density of sampling in regional geochemistry will be reduced.

In the priority areas for prospecting, a second generation of airborne geophysical survey or ground prospecting of integrated geophysical and geochemical methods will be launched systematically in conjunction with a 1:50 000 scale regional geologic survey. For the general survey, it will be on a scale of 1:50 000–1:25 000, while for the detailed survey, it will be 1:10 000 or even larger. With respect to the anomalies discovered during prospecting, they must be fully examined and evaluated in order to select potentially promising anomalies for timely confirmation by drilling. With fresh data obtained from the confirmation, the interpretation will be updated.

In the stage of evaluation and exploration of the deposits, ground and borehole geophysics and geochemistry should be applied according to site conditions to support the solving of geological problems such as the burial depth of orebodies, mode of occurrence, morphology, relation of individual bodies in space, structures, etc. in order to guide the drilling plan (Sun 1987).

Special attention should be paid to the utilization of integrated information in searching for ore deposits, starting from the metallogenetic prognosis, the selection of target areas, up to the interpretation of anomalies. For this purpose, a comprehensive interpretation must be made of the geological, remote sensing, geophysical, and geochemical data, allowing them to supplement each other so as to base the interpretation upon more reliable evidence.

## GEOPHYSICAL AND GEOCHEMICAL INVESTIGATIONS IN HYDROGEOLOGY, ENGINEERING, AND ENVIRONMENTAL GEOLOGY

To meet the needs of the everyday life of the people and their social development, this field of geophysical and geochemical investigation is becoming increasingly important. In the arid and semi-arid plains of Northern China and some of the water-deficient cities and mountainous areas, geophysical methods have been successfully used to locate water-prolific areas, such as old channels, Quaternary aquifers, water-carrying fractures, karstified zones, etc., and to locate water wells in the light of the hydrogeological conditions, so that well completion rate is raised up to 80 to 90 percent and a number of groundwater sources is found. Geophysical methods have played an important role, also, in the delimitation of fresh-saline groundwater boundaries, classification of groundwater mineralization, and detection of some hydrogeological conditions, etc.

In geothermal projects of three important types located in Yunan-Tibet, Beijing-Tianjin, and Fujian-Guogdong regions, the geophysical methods and geochemical methods with Hg, As, and Sb as the main indicator elements are successfully used to locate geothermal reservoirs, and to define fractures controlling the distribution of geothermal energy.

After confirmation by drilling, some sources of thermal water have been discovered in a number of localities. There are also a lot of successful applications in the respect of engineering and environmental geophysical and geochemical investigations. We will carry on this kind of investigation in the future, laying emphasis on key construction projects of the country, important cities and regions of landuse management.

Over the last decade, geophysical and geochemical investigations by other industrial ministries of China have also made rapid development and achieved positive results. Furthermore, the MGMR has made considerable progress in the fields of instrumentation, methodological development, and computer application, but because of the limited space of the text, a detailed description has to be omitted here. In addition, geophysical and geochemical prospecting and exploration for energy resources and remote sensing, done by various departments and institutions of MGMR, are not included here.

## CONCLUSION

It is clear that we will be facing a series of difficult tasks in our future exploration and prospecting. Undoubtedly, advanced techniques of exploration, geophysics, and geochemistry will play a more and more important role. Hence, we should actively develop both methodology and technology, expand the scope of their application, strengthen their coordination with other areas of exploration, and strive for their higher effectiveness in solving geological problems in order to obtain better geological results of prospecting and thus social and economic benefits.

## ACKNOWLEDGMENTS

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# 63. Mineral Exploration in Brazil: Past and Present

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## ABSTRACT

In Brazil, mineral exploration can be divided into four major phases. The Phase of the Adventurers, from the 16th to the 19th century, was characterized by prospecting for gold and gemstones. The second period – known as the Phase of the Foreigners – began after gold production had declined and was responsible for the first scientific geological survey of the nation. This phase began in the early years of the 19th century and ended in 1907 with the founding of the Brazilian Geological Survey. This event marked the start of the third phase and was followed by the founding of DNPM in 1934. In the following decades, the principal government mineral exploitation companies were founded, the first aerial and geochemical surveys were carried out, and significant mineral deposits were discovered including the huge Carajas Mineral Province. In the period from 1970 to 1978, a vast program of geological mapping was executed by DNPM, followed by an almost total seven-year interregnum. The fourth phase began in September 1985 and is scheduled to last until 1999. The program to be implemented during this period consists of geological-geochemical mapping at scales of 1:100 000 and 1:50 000 of 2 100 000 km² of the country, aerogeophysics and mapping at a scale of 1:250 000 in the Amazon Precambrian areas, subsurface hydrogeological forecasting maps and metallogenic maps at a scale of 1:250 000, as well as other projects related to metropolitan areas, gold, gemstones, and mineral processing technologies.

## INTRODUCTION

Brazil has an area of approximately 8 500 000 km² composed mostly of Precambrian terrain. Just as in the cases of Canada and Australia, this factor classifies the country as a suitable site for metallic mineral deposits.

Since the nation's discovery in 1500, Brazilian geological research has gone through four distinct phases. The Phase of the Adventurers, the Phase of the Foreigners, the First National Phase, and the Present Phase. The most important mineral deposits were discovered in the final decade of the National Phase, transforming the Brazilian mineral sector into a very attractive investment target.

## THE PHASE OF THE ADVENTURERS

This phase lasted until 1811 and was marked by important discoveries of gold in Parana, Sao Paulo, Maranhao, and Minas Gerais, making Brazil the world's leading producer of gold (Carvalho 1984).

At almost the same time, significant deposits of gemstones, including topaz, aquamarine, beryl, tourmaline, diamonds, and emeralds were discovered in the states of Minas Gerais, Bahia, and Goias. A direct result of these discoveries was the settlement of such remote areas as the states of Mato Grosso and Para, located in the Amazon region.

Today, the report prepared by the early pioneers and explorers responsible for these discoveries are quite scarce and hard to come by.

## THE PHASE OF THE FOREIGNERS

This phase, which lasted from 1811 to 1907, was marked by the founding of the first geological institutions in Brazil, including the Royal Museum, now known as the National Museum, the Geological Commission of the Empire, which undertook the geological survey of the nation, the Ouro Preto School of Mines, which turned out Brazil's first mining engineers and is now 110 years old, and the Sao Paulo State Geographic and Geological Map Commission (Carvalho 1984).

During this phase, the greatest emphasis was given to coal, gold, and gemstone production, though iron ore deposits were also discovered in the states of Sao Paulo and Minas Gerais.

In 1854, the first geological map of Brazil was published in Austria, showing the general geological structure of the country. (Foetterie 1854, in Schobbenhaus *et al.* 1984).

## THE FIRST NATIONAL PHASE

This phase started in 1907 when the Brazilian Geological and Mineralogical Survey was founded as a subordinate organ of the Ministry of Agriculture. The organization's teams of geologists and engineers travelled throughout the most remote regions of the country and, in 1908, issued a general geological map showing the principal mineral features and potentials of Brazil (Cavalcanti 1908, in Schobbenhaus *et al.* 1984).

In 1934, the first Mining Code was issued and the Geological and Mineralogical Survey was trans-

formed into the National Department of Mineral Production (DNPM). With these measures, the mining sector finally received a definitive structure.

However, it was only in the period from 1934 to 1970 that the government resolved to give due attention to the mining sector. The Companhia Vale do Rio Doce was given responsibility for iron ore exploitation, while PETROBRAS was charged with the field of oil, and the National Nuclear Energy Commission took on the task of developing the country's nuclear mineral deposits.

In 1960, the Ministry of Mines and Energy was created and absorbed DNPM as a subordinate organ.

Four events occurred in the period which contributed significantly to the immense geological surveys that were carried out in the following 10 to 15 years: creation of the first five schools of geology; initial systematic geological mapping projects; discovery of the Carajas iron ore deposits and the founding of the Mineral Research and Resources Company (CPRM).

By that time, oil production had already begun in the northeast, iron ore and manganese ore were being produced in Minas Gerais, Rondonia was producing cassiterite, and gold reserves were being exploited in many areas of the country.

In the 1970s, 42 percent of the nation's surface area was researched through geological mapping on a scale of 1:250 000, while 12 percent was mapped at a scale of 1:100 000. (Figures 63.1 and 63.2). In

the Amazon region, the RADAM Project carried out a rapid geological survey at a scale of 1:1 000 000 (Departamento Nacional da Producao Mineral 1985). The principal methodology used was aerial survey and two major aeromagnetic/cintilometric projects deserve particular attention: The Brazil-Federal Republic of Germany Project, which covered the State of Minas Gerais, and the Brazil-Canada Project, taking in part of the states of Goias and Para (Figures 63.3 and 63.4; Table 63.1).

As a result of these activities, close to 100 very important mineral deposits were found, most of which are now in production (Departamento Nacional da Producao Mineral 1985). In the Carajas region, an incredible mineral province with a diameter of no more than 100 km was discovered and is known to contain large deposits of manganese, tin, copper, zinc, wolframite, bauxite, and nickel together with already measured deposits of iron ore. Uranium was discovered in the states of Bahia, Ceara, and Goias; tin and gold in many areas of the Amazon region; phosphate in the central region of the country; potassium in the northeast; nickel, chromite, asbestos, and copper-zinc sulphide in Goias; oil on the continental shelf; and new coal reserves in the south (Figures 63.5, 63.6, 63.7, 63.8)).

Table 63.2 provides an idea of how the nation's major mineral reserves have developed as a result of the investments made during the period (Departamento Nacional da Producao Mineral 1972, 1986).

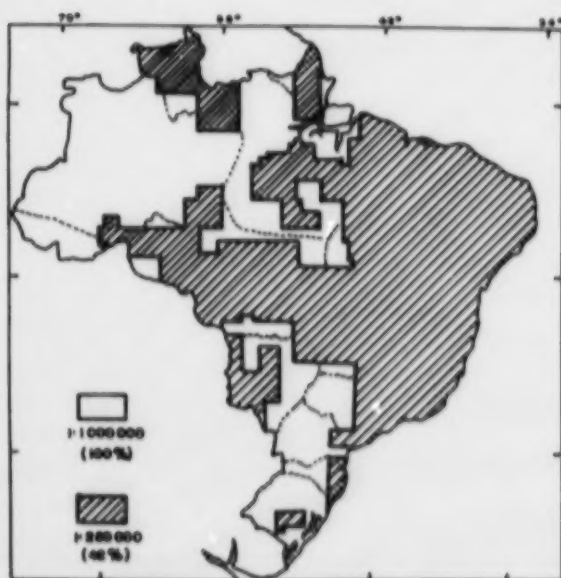


Figure 63.1. Geological cartographic coverage at scales of 1:1 000 000 and 1:250 000, up to 1985.

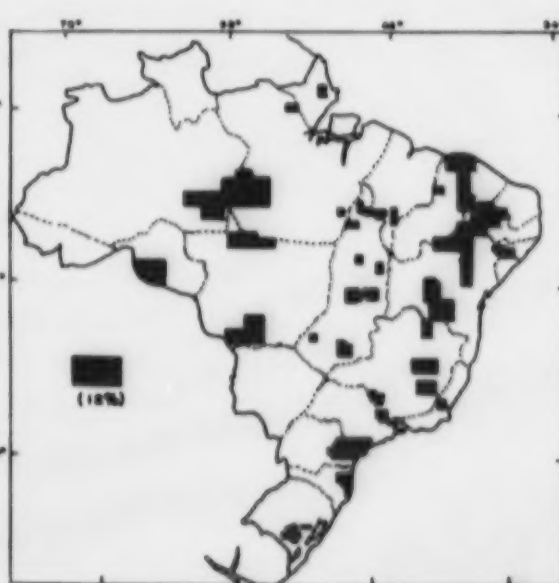


Figure 63.2. Geological cartographic coverage at a scale of 1:100 000, up to 1985.

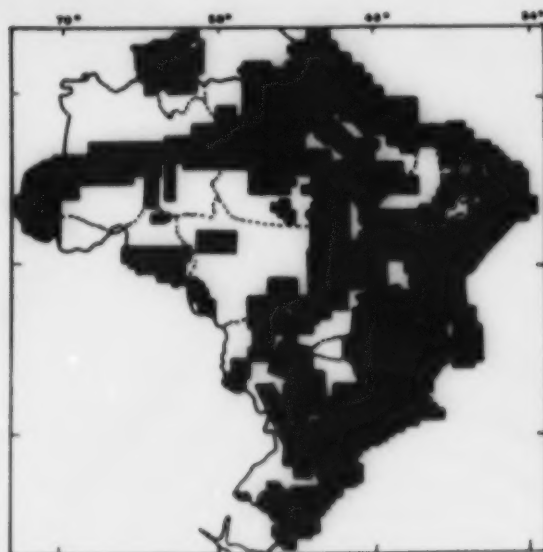


Figure 63.3. Airborne magnetic survey coverage up to 1985.

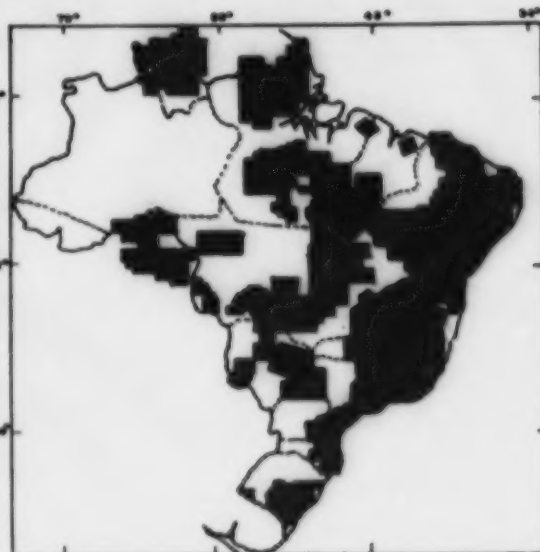


Figure 63.4. Airborne radiometric survey coverage up to 1985.



- |                                       |                                       |
|---------------------------------------|---------------------------------------|
| 1- CANINDÉ SÃO FRANCISCO - (Cu/Ni/Cs) | 15- SÃO FELIX - XINGU - (TIN)         |
| 2- BOM JARDIM - (COPPER)              | 16- MIRACU - (TIN)                    |
| 3- MARABÁ - (Cu/Au)                   | 17- NOVA ROMA - (TIN)                 |
| 4- MARABÁ - (Cu/Au)                   | 18- M. ALESSRE - GOIÁS - (TIN)        |
| 5- MARA ROSA - (Cu/Au)                | 19- NOVO ARIÃO - (TIN)                |
| 6- MARABÁ - (COPPER)                  | 20- ADRIANÓPOLIS - (Pb/Zn)            |
| 7- PALMEIRINHO - (COPPER)             | 21- MHAMUNDA - (ALUMINIUM)            |
| 8- PARACATU - (Pb/Zn)                 | 22- CACHOEIRA DE MACACU - (ALUMINIUM) |
| 9- SOA VISTA - (TIN)                  | 23- AURORA - (COPPER)                 |
| 10- MIRACU - (TIN)                    | 24- MARABÁ - (COPPER)                 |
| 11- PORTO VELHO - (TIN)               | 25- CANAQUÁ - (Pb/Zn)                 |
| 12- SÃO FELIX - XINGU - (TIN)         | 26- ARAGUINHA - (TIN)                 |
| 13- SÃO FELIX - XINGU - (TIN)         | 27- ITAITUBA - (TIN)                  |

Figure 63.5. Main deposits of non-ferrous metal ores discovered in the period 1970 to 1978.

- |                                 |
|---------------------------------|
| 1- SIRIRI - (SULPHUR)           |
| 2- PATOS DE MINAS - (PHOSPHATE) |
| 3- ANITÁPOLIS - (PHOSPHATE)     |
| 4- ITAIA - (PHOSPHATE/URANIUM)  |
| 5- ALMANORA - (PHOSPHATE)       |
| 6- ADRIANÓPOLIS - (FLUORITE)    |
| 7- ITABORAÍ - (FLUORITE)        |
| 8- AVEIRO - (SYNTHETIC)         |
| 9- CONTERAS-SINORÁ - (GARNET)   |
| 10- GUAXANDUBA - (VERMICULITE)  |
| 11- BOTUPORÁ - (GARNET)         |
| 12- LAGARAR - (PHOSPHATE)       |
| 13- DIVERSOS - (AM/PE)          |

Figure 63.6. Main deposits of non-metallic mineral ores discovered in the period 1970 to 1978.

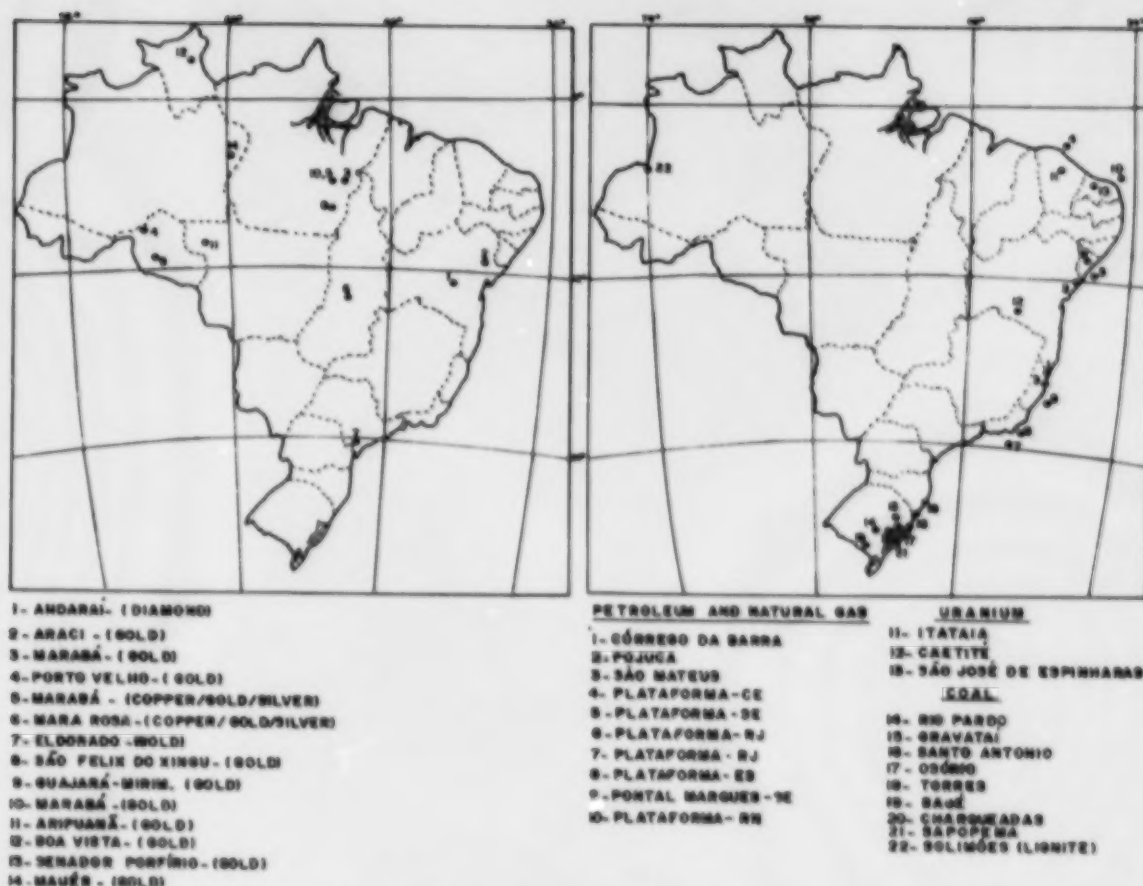


Figure 63.7. Main deposits of precious metals and diamonds discovered in the period 1970 to 1978.

Figure 63.8. Main deposits of energy mineral ores discovered in the period 1970 to 1978.

TABLE 63.1. GEOLOGICAL CARTOGRAPHIC COVERAGE EXISTING IN BRAZIL.

TYPE	SCALE	AREA(km ² )	%
1. Geological Maps	1:1 000 000	8 500 000	100
	1:250 000	3 500 000	42
	1:100 000	1 020 000	12
	1:50 000	INSIGNIFICANT	-
2. Geophysical Maps	VARIOUS	5 440 000	60
3. Metallogenic Maps	1:5 000 000	8 500 000	100
	1:250 000	2 520 000	30
	1:100 000	-	-



TABLE 63.2. DATA OF RESERVES (PROVEN AND ESTIMATED) AND PRODUCTION IN 1971 AND 1985; 1 - METAL, 2 - TON, 3 - CONCENTRATE.

	1971		1985	
	RESERVES (1.000 t)	PRODUCTION (1.000 t)	RESERVES (1.000 t)	PRODUCTION (1.000 t)
Asbestos	5566	473	56 800	2255
Bauxite	388 000	583	2 508 003	9963
Cassiterite	71	3	122 488	44
Chromite	1877	319	11 771	722
Coal	3 264 063	5666	9 726 012	24 414
Copper (1)	513	5	8000	123
Fluorite	672	56	5994	69
Gold (2)	152	5	370	29
Iron	8 370 028	37 676	17 399 596	167 232
Lead (1)	210	26	300	28
Limestone	6 903 889	13 077	55 498 605	45 266
Magnesite	301 444	233	646 813	623
Manganese	96 660	2376	145 215	3516
Nickel (1)	334	2	4109	788
Oil	-	9897	-	31 869
Phosphate	222 928	74	1 862 036	4148
Tungsten (3)	210	1	2300	2
Zinc (1)	1474	24	3495	673

Source: DNPM 1972, 1986

Unfortunately, with the sole exception of PETROBRAS' production of energy minerals, geological surveys had been almost totally interrupted by 1978. In this period, the country practically restricted itself to consuming what had previously been discovered. As shown in Figures 63.9 and 63.10, almost no discoveries of real importance have been made since that time, with the exception of oil fields, coal/peat, and gold (some huge deposits, such as Serra Pelada). However, in 1982, DNPM began elaboration of the first Metallogenic and Mineral Resources Forecasting Maps on a scale of 1:250 000.

### THE PRESENT PHASE

In September 1985, DNPM presented the new Minister of Mines and Energy with a plan that had the objective of reinitiating the process of geological surveys. This plan has been approved and is now in operation (Bastos 1986).

This plan takes in six major programs:

1. A systematic Geological Mapping Program covering an area of 2 100 000 km² of the Amazon region through geological/geochemical maps at a scale of 1:250 000, together with 1 115 000 km² at a scale of 1:100 000 and an additional

900 000 km² at a scale of 1:50 000 in other areas of the country. Aerial surveys in the Amazon region will cover an area of 1 404 000 km². Hydric Resources Forecasting Maps and Metallogenic and Mineral Resources Forecasting Maps are also to be made and will cover various large areas of Brazil (Figures 63.11, 63.12, 63.13, 63.14; Table 63.3).

2. An evaluation of the gold and gemstone deposits now being worked by individual miners.
3. An Energy Mineral Resources (coal and peat) Program which is now being concluded in the southern part of Brazil.
4. The evaluation of raw materials for construction and industry in metropolitan areas, with the objective of bringing together sufficient elements to subsidize mining programs in urban areas.
5. A Northeast Region Program, which has the purpose of evaluating small, immediately exploitable mineral deposits, while measuring the hydric potential of that critical region.
6. An Amazon Region Program, including detailed specific studies in such sectors as the Carajas Program (850 000 km²), for the purpose of establishing parameters for the ordered settlement of these areas with maximum preservation of the environment.

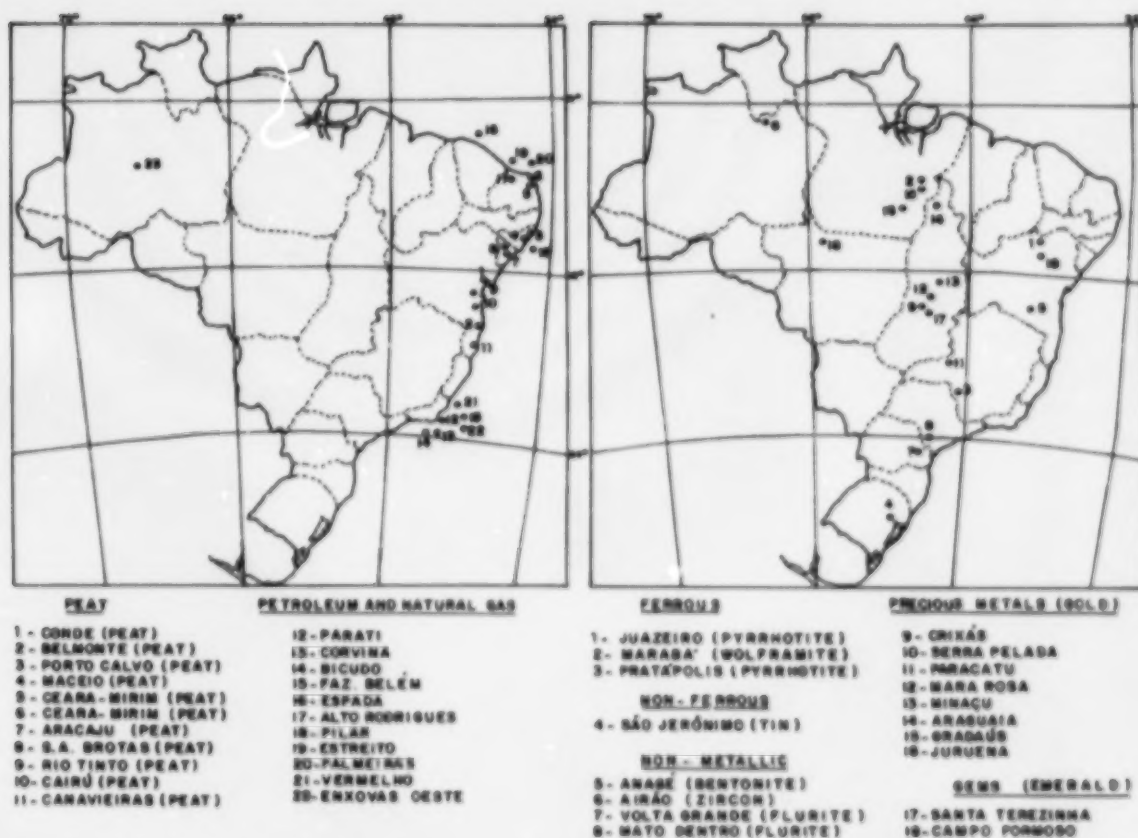


Figure 63.9. Main deposits of energy ore discovered in the period 1978 to 1983.

Figure 63.10. Main deposits of ferrous, non-ferrous, and non-metallic precious metals and gemstones discovered in the period 1978 to 1983.



Figure 63.11. Area to be mapped at a scale of 1:250 000, up to 1999.

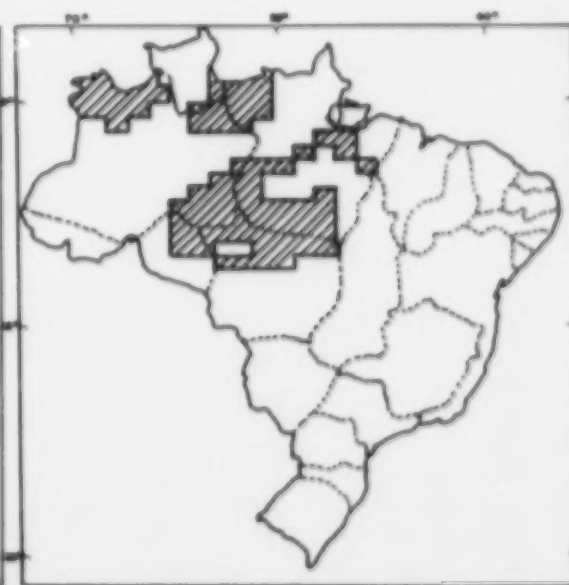


Figure 63.12. Area to be covered with aeromagnetic/radiometric survey, up to 1992.



Figure 63.13. Area to be mapped at a scale of 1:100 000, up to 1999.

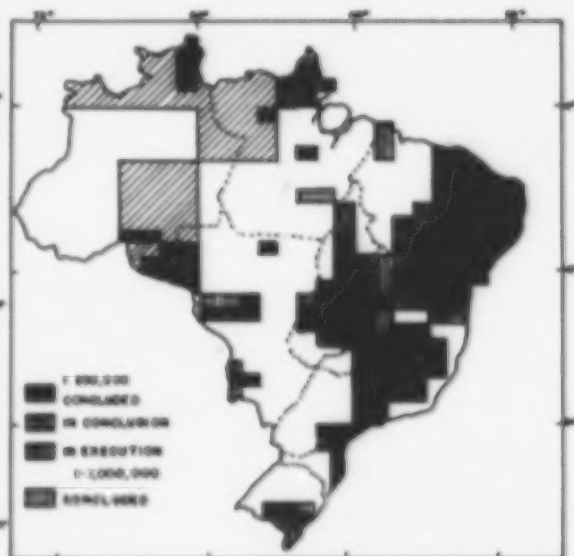


Figure 63.14. Metallogenic and Mineral Resources Forecasting maps at scales of 1:250 000 and 1:1 000 000.

TABLE 63.3. EXPECTED CARTOGRAPHIC PRODUCTION (1986-1999).

1. GEOLOGICAL/GEOCHEMICAL MAPS

SCALE	AREA (km ² )	COUNTRY %	COUNTRY'S TOTAL IN 1999 / %
1:250 000	2 100 000	24.7	66.7
1:100 000	2 115 000	24.9	36.9
1: 50 000	900 000	10.6	10.6

2. GEOPHYSICAL MAPS (AMAZON REGION)

Various	1 404 000	16.5	76.5
---------	-----------	------	------

3. HYDRIC RESOURCES FORECASTING MAPS

1:100 000	120 000	1.4	1.4
-----------	---------	-----	-----

4. METALLOGENIC AND MINERAL RESOURCES FORECASTING MAPS

1:250 000	3 180 000	37.4	67.4
1:100 000	2 115 000	24.9	24.9

## CONCLUSIONS

Although intense government-sponsored geological surveys have been carried out in the past, much of Brazil is an unknown mineral quantity, particularly in the Amazon region where jungle, climate, and the absence of infrastructure make it extremely difficult and expensive to undertake geological surveys. Examples of the vast potential of the region can be found in the immense Carajas Mineral Province, which was discovered in 1967 and is located on the edge of the region, and the results of the RADAM Project. In other areas of the country, specific geological environments indicate the existence of still undiscovered mineral deposits. In very few years, Brazil not only ceased importing but began exporting many types of ore, such as aluminum and cassiterite, while reducing its dependence on external sources of nickel, copper, zinc, lead, fertilizers, and oil. New gold deposits are being found almost every month, while already measured reserves of uranium, quartz, gemstones, limestone, manganese, iron, titanium, niobium, coal, and bauxite are sufficient for many decades of production.

It is our hope that the 1985 to 1999 Geological Mapping Plan will reveal new mineral deposits that will contribute significantly to the well-being not only of the Brazilian people but of all mankind.

## ACKNOWLEDGMENTS

We would like to acknowledge the General Director of DNPM, Jose Belfort dos Santos Bastos, for allow-

ing us to deliver this paper at Exploration '87, as well as the Associação Nacional de Empresas de Aerolevantamentos - ANEA, for the logistical support provided during this trip.

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## 64. The Canadian International Development Agency (CIDA) and the Mining Sector

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### INTRODUCTION

As an Agency, (CIDA) has specialized in the planning and delivery of international co-operation programs in several countries. It is customary to do continuous revisions to evaluate prevailing situations and to forge a clearer vision for the years ahead. In retrospect, advances in detection methods and surveying equipment in the last two decades have generated abundant data that can be used for a better understanding of global geology and mineral resources. Except for small parts of the earth, mineral belts, or metallogenic provinces, areas that have the greatest potential are known or have been identified on the crust of the earth. This has important implications for the planning of industrial development in different parts of the world for both consumer and producer countries.

Over the years, CIDA has supported programs addressed to the mining sector in four of its main branches. The programs are applicable to the entire spectrum of activities of the mining industry from data base acquisition to mineral exploration and development.

Funding of production units has been done mainly by the international financial institutions. The main efforts of the Canadian aid program have been concentrated on institutional support, technical assistance, data base acquisition, and training.

### MINERAL EXPLORATION

Since the beginning of this decade, the mineral and metal market has provided little stimulation for the search of additional supply sources, except for gold. Nevertheless, because of the importance of minerals in the economic development process, most countries have continued to support reduced activities in the sector. On a global scale, structural changes in the markets and the arrival of new production units result from economic development in different parts of the world, as technology becomes more widely available. The discovery of rich deposits near an expanding industrial market adds strength to economic growth and gives comparative advantages over traditional producers.

The lower degree of use of minerals and metals in the industrialized countries, and the uneven distribution of minerals and metals in the crust, are likely to favour the development of new supply sources

considering that the known existing resources are being rapidly depleted. This displacement of production centres will accentuate the need for raw materials from those countries which are less endowed with many of the necessary mineral resources to support their industrial development.

It is interesting to consider the statistics on world mine production and consumption for copper, lead, and zinc for the past ten years. From the plots of consumption in the following pages and mine production, consumption has increased steadily at an average rate of 1.33 percent for copper, 1.3 percent for zinc (slab zinc), whereas lead decreased by 0.9 percent (Figures 64.1, 64.2, and 64.3). The world is now consuming more minerals and metals of all kinds despite current economic stagnation and numerous substitutions. Mineral exploration will continue to play an important role in the future to assure the replacement of depleted reserves and to maintain the flow of raw materials for constantly growing needs.

Also, a comparison of the two curves for copper indicates that when consumption started to decrease in 1979, the inelasticity of production capacity can be seen by the continuously increased production volume which shows a slight decrease only in 1982. This resulted in serious accumulated surpluses and

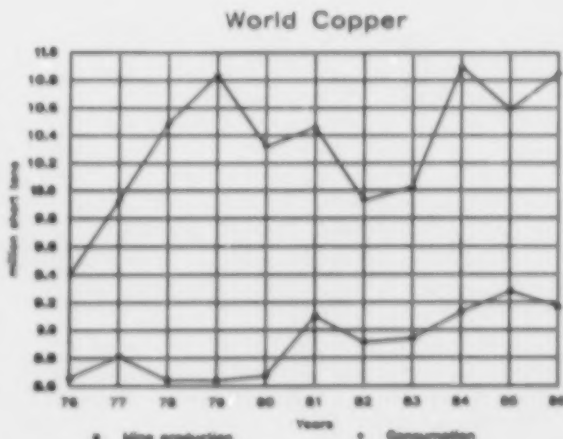


Figure 64.1. Graph illustrating world copper production and consumption in millions of short tons from 1976 to 1986.

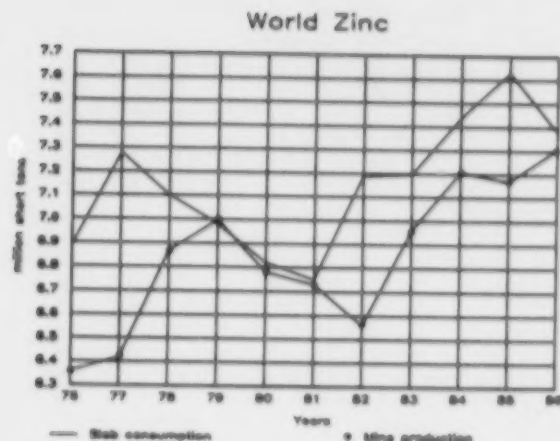


Figure 64.2. Graph illustrating world zinc production and consumption in millions of short tons from 1976 to 1986.

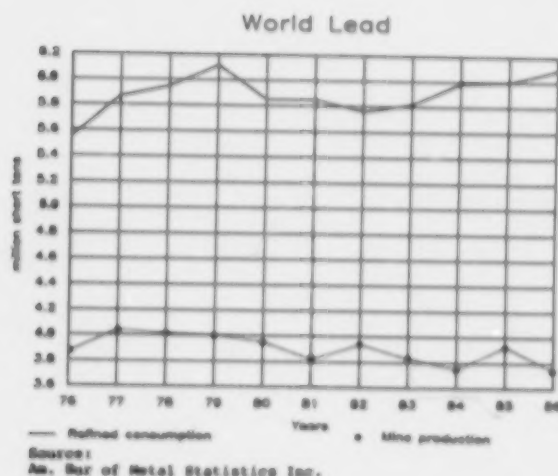


Figure 64.3. Graph illustrating world lead production and consumption in millions of short tons from 1976 to 1986.

the period of very low prices. The trends appear to be more positive for the immediate future.

## CANADIAN INTERNATIONAL DEVELOPMENT AGENCY

The Government of Canada supports a program of co-operation with Third World countries through a range of comprehensive delivery channels. The main thrusts of the Official Development Assistance program are concentrated in agriculture and food self-

sufficiency, energy, and human resources development. The assistance is provided through:

1. Bilateral programs (government-to-government) are in the countries of Africa, Asia, and the Americas.
2. Multilateral programs support United Nations agencies, international financial institutions, humanitarian institutions, and other international organizations.
3. Special programs encourage the initiatives of Canadian voluntary groups, institutions, and organizations to play a more active role in international development.
4. Business Co-operation programs sponsor initiatives of the private sector in support of business development and activities in Africa, Asia, and the Americas.

For the fiscal year 1986-87, the Official Development Assistance budget forecast amounted to \$2539 million. The major share of the budget, 42.3 percent, was allocated to the Bilateral programs, 34.7 percent to the Multilateral programs, 8.2 percent to Special programs, and 1.6 percent to the Business Co-operation programs.

In addition, the Department of External Affairs contributes to the regular budgets and voluntary funds of several multilateral organizations, while Canada Post and National Health and Welfare are also involved with international agencies active in development.

## BILATERAL PROGRAMS

For 1987-88, bilateral programs account for 36 percent of the Official Development Assistance budget, distributed in 105 countries throughout Asia, Africa, and the Americas. The general budget distribution among the three corresponding branches is 40 percent for Asia, 45 percent for Africa, and 14 percent for the Americas. Over the years, about 1.5 percent of bilateral program funds have been applied to projects directly related to the mining and metallurgy sector.

Currently, there are 16 projects in the mining and metallurgy sector distributed in ten countries, of which three are in Asia, eight in Africa and five in the Americas (Table 64.1).

The projects completed between 1970 and 1986 are listed in Table 64.2. The description of these projects provides an indication of the evolution of the governing policies of recipient countries on mineral resources.

The role played by Canada in the development of the mineral industry throughout the world was effected mainly through commercial activities by the private sector. Since our country is still the leader as an exporter of minerals and metals, future developments in the fields of minerals and metals have to be

TABLE 64.1. LIST OF CURRENT PROJECTS.

Country	Project Title	Description
<b>AFRICA</b>		
Botswana	Department of Mines	Technical assistance
Botswana	Geological Survey	Technical assistance Training
Botswana	Diamond Drillers training	Technical assistance Training
Ivory Coast	Line of credit	Technical assistance Training Equipment
Ghana	Gold Mining	Technical assistance
Niger	Recherche minière	Technical assistance Training
Niger	Développement du charbon	Technical assistance
Zimbabwe	Aeromagnetic Survey	Airborne geophysical surveys Technical assistance Equipment, training
<b>SOUTH AMERICA</b>		
Brazil	Small-scale Gold Exploration	Technical assistance Training
Brazil	Training in Mineral Exploration	Technical assistance Training, equipment
Brazil	Mineral Policy and Economics	Technical assistance Training
Jamaica	Metallic Mineral Survey	Geochemical survey
Jamaica	Bauxite Tailings pre-feasibility	Technical assistance
<b>ASIA</b>		
Bangladesh	Peat Pilot Project	Feasibility study
India	Line of Credit	Mining equipment
Thailand	Mineral Resources Development	Technical assistance Professional and technical training

considered in relation to prospective markets and world economic stability. Furthermore, the projects must be of developmental value and commensurate with the receiving capability of the recipient countries.

The projects cover activities in mineral exploration, development, and mineral production. The projects are carried out under agreements with governments or para-statal organizations. Of the 16 active projects, 13 are specifically applied to mineral exploration, two to development, and only one to the production of gold.

#### PROJECT DESCRIPTION

Only projects that directly concern mineral exploration are described in this section.

*Thailand: Mineral Resources Development Project.* This project, which is co-funded with the Asian Development Bank, was initiated several years ago by the Department of Mineral Resources of Thailand.

It consists of five major components, the first three of which are funded by the Bank under a loan agreement and the last two by a CIDA grant contribution. The components are listed as follows:

1. airborne geophysical surveys (using fixed-wing aircraft and helicopters) to carry out magnetic and radiometric surveys over the entire country; provision is also made for the flying of selected zones with an electromagnetic system
2. building of additional facilities, both in Bangkok and regional centres, to provide increased laboratory capacity and additional office space for the personnel
3. procurement of geophysical equipment for ground follow-up activities and on-the-job training; diamond-drilling equipment and road building equipment for target drilling
4. provision of technical assistance for the duration of the project in the fields of economic geology, geophysics, geochemistry, mineral economics, mineral legislation, mineral taxation and mining

TABLE 64.2. PROJECTS COMPLETED 1970-1986.

Country	Project Title	Description
<b>AFRICA</b>		
Botswana	Aeromagnetic Survey in Kalahari 1975-77	Airborne geophysical survey
	Kalahari Mineral Exploration 1982-84	Technical assistance Training Equipment
	Department of Mines 1981-84	Technical assistance Training
	Geophysical Exploration Phase I 1974-76 Phase II 1976-82	Airborne geophysical survey Technical assistance Training Equipment
Ethiopia	Technical Assistance for training in geology 1979-80	Technical assistance
	Omo River Project Phase I 1970-75 Phase II 1975-83	Photogeological maps Airborne geophysical surveys
		Technical assistance Training
		Technical assistance
Ghana	Tarkwa School of Mines 1970-73	Training
	Diamond Driller Training 1975-76	Training
Ivory Coast	Airborne geophysical Surveys 1973-78	Airborne geophysical surveys
		Technical assistance
Ivory Coast	Programme intercalaire 1980-84	Technical assistance
Kenya	Airborne Geophysical Survey 1975-80	Airborne geophysical surveys
		Technical assistance
	Development of the Mining Sector Phase II 1975-79 Phase III 1979-82	Technical assistance Training Equipment
Lesotho	Aeromagnetic Survey 1974-80	Airborne geophysical surveys
		Technical assistance
	Assistance to Small- scale Diamond Mining 1978-80	Technical assistance Equipment
	Diamond Mining Co-operatives 1981-83	Technical assistance
Mali	Coal Drilling Study 1981-84	Technical assistance
	Airborne Geophysical Study 1971-72	Technical assistance
Niger	Airborne Geophysical Survey 1973-74	Airborne geophysical surveys
Swaziland	Geochemical Survey Phase I 1975-77 Phase II 1977-78	Technical assistance Equipment
Rwanda	Prospection géo- physique 1981-85	Technical assistance
Tanzania	State Mining Corp. 1970-74	Technical assistance Training Equipment



TABLE 64.2. CONTINUED.

Country	Project Title	Description
<b>AFRICA (Cont'd)</b>		
Upper Volta (Burkina Faso)	Airborne Geophysical Survey 1970-74	Airborne geophysical surveys
Liptako-Gourma	Développement du Liptako Gourma	Airborne geophysical surveys
<b>SOUTH AMERICA</b>		
Bolivia	Comptabilité minière 1979-81	Technical assistance
Brazil	Goiás Mineral Resources Survey 1974-78	Airborne geophysical surveys
		Technical assistance
	University of Bahia	Training
	1975-79	Technical assistance
	Technical Assistance	Training
	MIC/STI 1982-86	Technical assistance
	Mineral Exploration	Training
	School 1982-84	Technical assistance
Colombia	SENA Mining Training Centre 1975-79	Training
	Feasibility Study	Technical assistance
	El Cerrejon 1982-83	Study
Guyana	Aerial Mineral Survey 1970-73	Airborne geophysical surveys and map-
ping		
Honduras	Technical Assistance to the Department of Mines and Hydrocarbons 1976-79	Technical assistance Training
<b>ASIA</b>		
Burma	Mineral Exploration 1971-74	Technical assistance Training
	Barite Mining Project 1979-81	Technical assistance Equipment
India	Khetri Copper Mining 1972-75	Technical assistance Equipment
	Geological Survey Equipment 1970-74	Equipment
Indonesia	Ombilin Coal Mine 1975-82	Technical assistance Training Equipment
Malaysia	Geochemical Survey 1976-80	Technical assistance Equipment
Pakistan	Aeromagnetic Survey 1973-76	Airborne geophysical surveys
	Baluchistan Coal Plant 1980-85	Equipment Technical assistance

regulations, handling of geodata, and mining information

5. training of Thai staff members of the Department of Mineral Resources in various fields of earth sciences to meet its requirements

The Agency uses the services of an executing agent to implement its project. In addition, the Geological Survey of Canada provides technical advice for the project and has agreed to assist the Department of Mineral Resources with the monitoring of the airborne geophysical surveys.

Over the five-year duration of the project, one of the principal roles of CIDA is supervision and quality control to ensure that the services offered meet the highest Canadian standards and fulfill the requirements of the recipient organization. It is the responsibility of the executing agent to provide the expertise that is requested by the Department of Mineral Resources within the fields of the technical assistance provided.

It is expected that the results of this work will be released by the Royal Thai government in support of the plan to develop the country's mineral resources.

**Botswana: Geological Survey.** This is a localization project implemented by an executing agent. Technical assistance is provided by three geophysicists in the Geophysics Division of the Department of Geological Survey, with specialization in hydrology and mineral exploration. In order to localize the Geophysics Division, a group of Botswana personnel is being trained in Canadian universities and will eventually assume the positions now occupied by the Canadian geophysicists.

Under the authority of the Director of the Geological Survey, the Canadian geophysicists are performing all the duties required for this kind of operation, including field work supervision, evaluation of reports, monitoring of airborne surveys, and data processing and storage.

**Diamond Drillers Training:** This is a small project for which the agency provided the technical assistance of one master driller for a period of three years to train Botswana personnel in drilling techniques. Following the successful completion of the on-the-job training, three trainees are at the present time furthering their experience in Canada by taking courses in the maintenance of hydraulics systems and diesel engines.

**Ivory Coast: Line of Credit.** Under this multisectoral line of credit, there is a provision for technical assistance in mineral exploration, training, and procurement of equipment to the para-statal corporation responsible for mineral developments in the country. This is really a continuation of the program started over ten years ago with countrywide coverage using airborne magnetic and radiometric surveys. Also, at the beginning of the decade, the agency provided a combined airborne magnetic and electromagnetic (INPUT) survey over selected parts of the country. Technical assistance in geophysics and diamond drilling was provided along with the purchase of both geophysical and drilling equipment. The services were applied to on-the-job training during an ongoing exploration program.

**Niger: Recherche minière (Mineral Prospecting).** The project began in 1979 with the provision of technical assistance and training and the supply of equipment to work mainly on an occurrence of phosphate. Feasibility studies were based on drill results and laboratory tests. Additional work was also done on gypsum and limestone deposits. This was later followed by a second phase, during which the emphasis was placed on mineral exploration which led to surface exposures of gold mineralization that have attracted considerable interest lately. The exploration methods were ground geophysics and geochemistry, sampling and drilling, all carried out by the para-statal organization. The second phase also

included several scholarships for education and training in Canada.

This gold occurrence west of Niger river prompted a rush estimated at 25 000 people who reportedly extracted about \$35 million worth of gold during the first year. Early in 1987, the Nigerian government invited the private sector to apply for concessions.

The project will be extended further to provide assistance with the development and evaluation of the potential deposits.

**Niger: Développement du charbon (Coal Development).** This is a new project integrated within the energy development plan of the country aimed at reducing the dependency on fuel wood and protecting the environment. Technical assistance will be provided to assist in the mapping, drilling, and evaluation of mineable reserves of coal in those parts of the basins closest to the main consumption centres.

**Zimbabwe: Aeromagnetic Survey Project.** Implementation of this project started in 1983 with the first two airborne surveys: 90 000 line km of aeromagnetic survey and about 20 000 line km of combined magnetic and electromagnetic (INPUT) survey of selected areas within that of the aeromagnetic survey. Geophysical and drilling equipment was supplied with the collaboration of an executing agency, which was also responsible for the provision of technical assistance in economic geology and geophysics and on-the-job training.

In this case, the executing agency was directly responsible for the physical execution of the ground follow-up programs. The airborne geophysical data were re-interpreted using satellite imagery and available information on geology and mineral occurrences. Detailed ground geophysics, magnetometer, electromagnetometer, and induced polarization were used over the conductive zones to measure their properties. Geochemical soil sampling on some of the grid lines helped with the selection of targets for drilling.

In the area flown, which covers most of the volcanic belt, the rocks with the lowest susceptibility correspond with the basic volcanic rocks. The rocks with intermediate susceptibilities are the granitoid masses. Those with the highest susceptibilities indicate either iron formations or ultrabasic rocks. In order to enhance the results, the data was processed to determine the best methods that would give results comparable to those of similar areas in Canada. The magnetic map obtained from a reduction of data to the pole gives an excellent account of the geology and indicates many features that were likely unknown. Moreover, the magnetic data reduced to the pole were also produced at a scale of 1:100 000 at the same scale as the geological maps of the country.

All geophysical methods were very successful in detecting the target conductive zones. Throughout the project area, the only limitation appears to be the high soil conductivity in the first 20 m due to the surface alteration.

**Brazil: Small-Scale Gold Exploration.** Although the name is exploration, this training project applies to mining engineers, metallurgists, and geologists working in gold mining operations. Under the management of an executing agent, Canadian specialists will visit the designated para-statal institutions for periods of up to three months about twice a year over a period of three years. The executing agency will also be responsible for the implementation of the training program that will be defined in consultation with the Brazilian professionals.

**Brazil: Training in Mineral Exploration.** This project with one of the provincial para-statal organizations has four main components. These are:

1. the provision in Canada of specialized training in Canadian mining districts, universities, and governmental geological institutions for Brazilian geologists and mining engineers
2. the provision of Canadian technical assistance in relation to mineral exploration programs
3. the provision of equipment and library materials to facilitate mineral exploration programs
4. project management and implementation by a designated executing agency

**Brazil: Training in Mineral Policy and Economics.** The project has four main components. These are:

1. training in mineral policy and economics through specialized courses, seminars, and practical attachments at universities and government institutions in Canada
2. training in Brazil by short-term Canadian specialists
3. the provision of one scholarship in mineral economics with a Canadian university
4. project management and implementation by the designated executing agency

**Jamaica: Metallic Mineral Survey.** The implementation of this project was started at the end of 1985 with the first component consisting of a regional reconnaissance geochemical survey. In the areas known to have greater potential for metallic minerals, stream sediments, silt, and heavy minerals were collected at an average density of one site per 1.3². It is expected that the results of this initial phase will be released before the end of this year.

There is a provision for two additional phases to the project, that are to be defined on the basis of the results previously obtained.

1. a follow-up program of more detailed exploration of selected areas, using appropriate

geochemical and geophysical methods and geological mapping

2. detailed exploration of selected areas, involving more extensive trenching and diamond drilling

**Jamaica: Bauxite Tailings Pre-feasibility.** This project was initiated by the Industrial Research Development Corporation which identified the presence of rare-earth metals in the bauxite tailings of the major operations in the country. A project feasibility study was carried out by a Canadian company which concluded negatively concerning the market and the extraction process. The project was discontinued.

## MULTILATERAL PROGRAMS

Canadian funding for multilateral projects is channeled through international financial institutions, United Nations agencies, and other organizations involved in development and research. Each organization is responsible for the administration of projects. Canada, as a contributor, participates in the deliberations of the governing bodies that direct the organizations' policies, programs, and budgets.

The United Nations agencies are the most active in practically all phases of mineral exploration throughout the world. It is only in the last few years that the financial institutions have supported some projects directly addressed to exploration and data base strengthening.

## SPECIAL PROGRAMS

Through its support for the initiatives of the Canadian voluntary sector and non-profit institutions in international co-operation, Special Programs tap the creative resources of the non-governmental community and encourage joint ventures and exchanges with their counterparts in the Third World.

Different levels of co-operation in the mining sector have been sponsored by these organizations. It ranges from assistance to industries to participation in university programs and voluntary co-operation.

## BUSINESS CO-OPERATION PROGRAM

This Branch, together with other existing bilateral programs, assists Canadian exporters to penetrate new markets in developing countries and supports the Canadian private sector seeking opportunities for investment, joint ventures, and transfers of technology to these markets. By encouraging the business community to increase its investments in the Third World, the Agency enables Canadian firms to make the most of opportunities in the expanding markets of Africa, Asia, the Caribbean, and Latin America, while simultaneously making an important contribution to development.

Activities in the mining sector are very diversified in this program. It fosters the development of

joint ventures between Canadian companies and corporate organizations in developing countries and provides assistance for feasibility studies. Only the contributions to transfer of technology and training, like the assistance provided for this meeting, can be directly linked to mineral exploration.

## CONCLUSION

The Agency contributes directly and indirectly to a broad spectrum of activities in the mining sector. Mineral exploration projects are almost exclusively supported by bilateral programs.

Considerable research is required to adapt the most up-to-date technology to local conditions of

developing countries in the fields of geophysics and geochemistry. While geology presents many similarities with different parts of Canada, widespread surface alteration and lateritization can impose some limitations to the various methods.

Lately, geophysical data processing has successfully produced the equivalent of geological maps that show much better resolution of the geology than any field mapping project or compilation of existing geological information. The latter, however, is essential to the full understanding of the data. Data processing still holds considerable promise to improve interpretation that will guide the search for mineral deposits in the future.



# 65. The Mineral Resources Program of the United Nations Department of Technical Co-operation for Development

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## ABSTRACT

The Department of Technical Co-operation for Development (DTCD) is the United Nations' (UN) principal agency for mineral resource exploration and development. Operating mainly in countries where other sources of finance and expertise for mineral sector activities are insufficient or lacking, the programs have, since 1959, totalled US\$250 to 300 million, mainly from United Nations Development Program funds.

Ore deposits valued at some tens of billions of dollars have been discovered, including porphyry coppers in Mexico, Panama, and Malaysia; gold in Tanzania; and tin-tungsten in Burma. Recent finds include a new volcanogenic base-metal sulphide province in Burkina Faso and a major gold field in Mali. A complete airborne geophysical survey of Malawi has also been executed.

Current DTCD activities comprise 60 mineral projects in 41 developing countries, mainly in Africa and Asia, with total aid budgets of US\$51 million. Annual budgets total about \$15 million from UN sources, plus the equivalent of some \$10 million in government services and facilities.

Activities cover the whole spectrum of mineral resource development from policy and legislation through exploration and evaluation to mining, processing, and marketing. They also include support work such as training, establishment or strengthening of government facilities, introduction of new technologies, and specialized advisory services. The DTCD's objective is to identify mineral resources and promote their development by encouraging private sector follow-up and/or, where appropriate, by assisting state mining agencies. The process is described, with examples.

## INTRODUCTION

The Department of Technical Co-operation for Development (DTCD) is the United Nations' (UN) principal agency for mineral resource exploration and development. The DTCD's mandate covers Development Planning, Development Administration, Public Administration and Finance, and Population and Statistics, but half of its annual delivery of technical assistance services (which totaled US \$146 million in 1986) comes from the Natural Resource Sector. This sector is the responsibility of the DTCD's

Natural Resources and Energy Division, comprising separate Branches for minerals, water, and energy (which includes hydrocarbons, geothermal, solar, wind, biomass, etc.), as well as an infrastructure branch covering remote sensing, cartography, and public works. The United Nations Development Program (UNDP) funded \$103 million of the \$146 million volume; the remainder came from the UN Fund for Population Activities, from "Trust Funds" provided by individual governments, and from the UN's "Regular Program" budget.

Currently, the total annual project budget of the DTCD Minerals Branch is running at about \$17 million (mid 1988), down from around \$20 million in 1982, but is now on the rise again.

## DTCD MINERALS BRANCH—OBJECTIVE

The objective of the DTCD Minerals Branch is the promotion of mineral resource development, by whatever means are appropriate to the country concerned. Its programs are designed to help both developed and developing countries, by identifying projects worthy of investment. To this end, it is engaged in activities across the whole spectrum, from mineral policy, legislation, and contracts at one end, through grass roots and detailed exploration, evaluation, feasibility, investment promotion, mining, and processing, and on into marketing. Because of financial constraints — few UNDP projects have budgets in excess of \$2 to 3 million — most mineral projects are in the upstream end of the process, that is, in systematic exploration and pre-investment work. The DTCD's contribution to mining and processing is generally confined to providing expert advice, training, or specialized equipment.

The DTCD also engages heavily in "institution strengthening" projects: establishing and improving government support facilities such as laboratories and pilot plants, arranging specialized training courses, introducing new technologies such as micro-computer applications, and supplying expert advisors, both short-term consultants and longer term residents. The orientation is commercial, rather than towards research or formal academic education.

The UNDP's technical assistance is offered only to government departments or government-owned agencies, not to private companies. Training and participation by national personnel are strongly emphasized in all DTCD projects. The aim is to equip

the government to undertake mineral resource development work by itself.

## ORGANIZATION OF THE MINERALS BRANCH

The Mineral Resources Branch of the Natural Resources and Energy Division is located at UN Headquarters in New York City. Under a Chief of Branch it comprises a group of about ten internationally recruited specialist advisors: economic geologists, mining engineers, a geophysicist, a drilling engineer, a computer specialist, and a mining lawyer. These technical experts work in teams with an administrator and a secretary, managing projects through the UNDP office in the developing country concerned, and supported at DTCD Headquarters by specialized departments for recruitment, fellowships, contracts and procurement, and accounting. The DTCD has no in-house technical support services, such as laboratories. Each team runs about 10 to 15 projects, usually grouped geographically.

When a government requires technical assistance in the mineral sector it requests, through the UNDP office, a visit by a DTCD advisor. The countries that make such requests are mainly ones where other sources of financing and assistance are not readily available, like certain African countries, where the private sector is poorly represented or absent. The DTCD can provide access for such countries to international experience; its services are also in demand whenever an independent, objective opinion is required. The DTCD tends to operate especially in places where mining is confined to the public sector or where grassroots exploration is regarded as too risky by private mining companies. By contrast, countries with flourishing mining sectors, like Indonesia and Brazil, or that receive a lot of attention from the international community, like China, tend to have few or no UN mineral projects.

The DTCD advisor, in consultation with the Government and the UNDP, then defines a detailed program of technical assistance and embodies it in a "project document": a tripartite legal contract between the Government (which receives the assistance), the UNDP (which finances it) and the DTCD (which executes it). Following signature, which can take many months in some cases, the DTCD recruits from international sources and sends to the field the required specialized personnel (geologists, chemists, drillers); arranges the subcontracts, e.g. for control assays; purchases the equipment (field, laboratory, office equipment); and arranges the training courses.

Ten or fifteen years ago the DTCD often had large expatriate teams of experts in the field, doing most of the work for the Government; now many DTCD projects are managed and run in the field by the country's own geologists and engineers, guided

and assisted by periodic visits from the advisor and from highly specialized short-term consultants. This evolution from 90 percent resident experts and 10 percent consultants in the past, to today's 15 percent residents and 85 percent consultants, reflects the success of UN, bilateral, and other technical assistance programs over the years, together, of course, with the Governments' own endeavours.

## UN/DTCD MINERALS BRANCH PROJECTS: HISTORY AND ACHIEVEMENTS

Since 1959, the DTCD has expended some US\$250 to 300 million on hundreds of mineral projects, in about 75 countries worldwide. About 1.1 million line kilometres of airborne geophysical surveys have been flown, and more than three million geochemical analyses performed. This work has assisted in the discovery of ore deposits whose contents have been valued at many billions of dollars. They include porphyry coppers in Mexico (La Caridad), Panama (Cerro Petaquilla, which led to the Cerro Colorado deposit) and Malaysia (Mamut); the Buck Reef gold deposit in Tanzania; and the Heinze Basin tin-tungsten deposit in Burma.

In 1982 a major zinc-lead-silver volcanogenic massive sulphide deposit was discovered by geochemistry in a UN project in Upper Volta (now Burkina Faso). This, like the Cerro Petaquilla discovery, has also opened up a major new metallogenic province for further exploration: the DTCD is following this up by INPUT surveys in Burkina Faso and, it is hoped, in Niger also.

In 1985 another DTCD mineral project in the neighbouring country of Mali identified widespread gold mineralization southeast of the capital, Bamako — again by geochemistry. With continuing assistance from the DTCD, the Government of Mali has recently signed a joint venture agreement with Broken Hill Proprietary's Utah Minerals subsidiary for an initial \$1.5 million investment to explore and develop the area's resources.

Other recent achievements include a project in the Philippines which has trained national personnel in the latest techniques of epithermal gold exploration and demonstrated its effectiveness by identifying several targets that have attracted the interest of domestic and foreign mining companies. Two gold deposits discovered by the UN in Haiti have also attracted private interest.

In Somalia a major deposit of sepiolite has been evaluated (about 10 million tons at perhaps \$60/ton), and in Mozambique heavy mineral beach sands discovered by the DTCD project are being investigated by a private company. In recent years, the DTCD has conducted extensive airborne geophysical surveys in several countries: Mauritania, Rwanda (in co-operation with the Canadian International Development Agency (CIDA)), Cameroon, North and

South Yemen, and Malawi. All of these have potential for leading to economic targets; they also provide essential lithologic and structural data often unobtainable by other means.

A project in Paraguay resulted in the preparation of geologic, hydrogeologic, and metallogenic maps of the country, to be used both for future mineral exploration and for regional planning purposes.

The DTCD mineral projects also address non-metallic or industrial minerals. Although perhaps not as glamorous as a big metallic find, industrial minerals are commonly simpler and cheaper to develop, and can contribute significantly and quickly to national economic growth, providing employment, building infrastructure, and often substituting for hard-currency imports. For example, a DTCD project in Jamaica has discovered high calcium limestone and marble deposits which have attracted investor interest, and will help to diversify away from the present heavy reliance on bauxite. In the West African country of Benin, deposits of gravel, clay, and marble were evaluated for the local construction industry.

A recital of these and the many other achievements in the area of exploration would overlook other very important facets of the DTCD minerals program. These include training in every aspect of earth science and management, from UN experts on the job, by study tours to mines and laboratories overseas, and through fellowships in formal, specialized instruction courses. Institution building and the transfer of technology are other major activities: provision of equipment of all kinds, and advice and instruction in how to use it (in 1986 the Minerals Branch spent \$3.2 million on equipment alone), or establishment of government units for specialized tasks, e.g. the creation of a modern, computer-equipped feasibility study unit in the Indian Bureau of Mines. The advent of powerful, low-cost microcomputers has enabled the DTCD to introduce EDP techniques in Government Mines Departments of many developing countries: all of the DTCD's larger projects now include computer applications. They range from provision of a single IBM-PC to perform simple word-processing and data management tasks in a West African country, to design of a complete national mineral database for India.

## CURRENT MINERALS BRANCH ACTIVITIES

As of mid 1988, the DTCD Minerals Branch is operating close to 70 projects in 45 countries worldwide.

The projects have total US dollar budgets of some \$5 million (\$17 million to be spent in 1988). In addition, government funds of about two-thirds of these amounts should be counted in: the government contributions cover the services of national personnel engaged in the projects, government

equipment and services of all kinds used by the project, and the use of government facilities. Thus, the effective annual project budget total is nearer to \$25 to 28 million, perhaps half of which could be described as exploration related. Twenty-nine of the projects (total UNDP contribution \$35 million) are in Africa, 15 in Asia and the Pacific (\$12 million), 16 in Latin America and the Caribbean (\$7 million), 3 in Arab countries (\$2 million). Project budgets range from as little as \$12 000 for a visit by a single consultant, to as much as \$4.6 million for a major, long-term, integrated exploration project in Mali.

Besides these formal projects, the Branch engages in a variety of other activities.

In 1988 some 80 advisory missions by specialist DTCD advisors and consultants will be undertaken. These missions were mostly financed from the Department's own "Regular Program" budget, reflecting growing developing country requirements in such fields as computer applications in mineral exploration and evaluation, investment promotion, mineral development legislation and contract negotiations, and mineral sector planning and institution strengthening.

Another significant activity of the DTCD Minerals Branch is the presentation of professional seminars and workshops on specialized topics of importance to the international mineral sector. These are always organized in co-operation with, and with participation from, the host government of the country concerned. For example, in 1986 the DTCD arranged a seminar entitled "The Applications of Electronic Data Processing Methods in Mineral Exploration and Development" in Sudbury, Ontario, with the co-operation of CIDA, the Ontario Ministry of Northern Development and Mines, and Laurentian University. The proceedings of that seminar are an important reference on the subject. In 1985, the DTCD organized a seminar in India on gold. In 1987, the DTCD held a seminar in Budapest on "The Role of State Enterprises in the Solid Minerals Industry in Developing Countries". In the last three years a total of nine seminars have been held in six different countries.

Specialized earth science training courses are regularly organized by the DTCD in co-operation with donor governments, such as the USSR.

The DTCD also publishes the "Natural Resources Forum", a quarterly journal of economic, technical, and policy issues concerning energy, minerals, and water resources, and the periodical "Natural Resources and Energy Newsletter".

From 1980 to 1983, a series of missions were organized to 39 developing countries who requested DTCD assistance to assess the status of their mineral inventories and to estimate their needs for exploration and development expenditures. The resulting assessment reports are still valuable as a source of earth science and mineral deposit data for development purposes.



## DEVELOPMENT OF DEPOSITS

Finally, the DTCD co-operates extensively with other organizations. As described above, its projects are essentially joint operations with government agencies. The DTCD may also operate in parallel with others, as in Rwanda, where the DTCD flew an airborne survey of one half of the country, and CIDA flew the other half; or in the Philippines, where the project laboratory performed all the assays for a Japanese bilateral exploration program. The DTCD may also supply independent technical support for programs undertaken by others, for example, in the Yemen, where it has provided supervision and quality control for an airborne geophysical survey financed by the Arab Fund; or in Ghana, where the DTCD is monitoring for the Government the performance of the Canadian Consulting Group which is rehabilitating the operations of the State Gold Mining Corporation.

One of the DTCD's major objectives is to assist governments in turning deposits into mines. United Nations' policy in undertaking mineral exploration is to carry out investigations until a potentially economic mineral deposit is located. The Government of the country is then asked to decide whether to continue investigations using United Nations technical services, or by using private, or other public sector, services to carry the work beyond the preliminary feasibility stage.

In the case of the UN's Perkoa discovery in Burkina Faso, the Government elected to continue the preliminary evaluation work itself, and subsequently secured \$8 million in World Bank financing for a pre-feasibility study, which was executed by a consortium led by Pennarroya. Their conclusion was negative, but a second study by a Canadian group is more encouraging. In any case, additional discoveries are expected to result from the DTCD's planned INPUT survey, to be financed by the Arab Fund, and these could change the overall economics.

It is a principle of the United Nations Development Program, and thus also of the UN's mineral program, to encourage private sector follow-up and

development. As noted above, the UN has assisted the Government of Mali in reaching a mutually satisfactory agreement with BHP-Utah for exploration of gold mineralization found by a DTCD project in that country. In Ghana, the Minerals Branch helped the Government negotiate a management contract with a Canadian consortium led by Cominco, for the rehabilitation of the State Gold Mining Corporation, and is now monitoring their activities and facilitating their co-operation. The DTCD also attempted, without success, to find investors for the Huemueles silver/base-metal deposit explored by the Revolving Fund in Argentina, and is currently assisting the Government of the Dominican Republic in negotiations with Falconbridge over its nickel project.

The DTCD is now vigorously involved in investment promotion activities in a number of countries. For many years it has provided advice and assistance in the general area of mineral policy, both by drafting or modifying mining legislation and regulations so as to create a more attractive environment for investment, and by helping Governments negotiate with foreign companies, for example by supplying legal and mining consultants and more recently by providing computer support for the financial analysis of proposals.

The DTCD project and advisory reports — and DTCD advisors — have also provided an invaluable source of technical information on developing country mineral resources, available for consultation, both in the field and at United Nations Headquarters.

The DTCD is now increasingly engaging in more specific investment promotion, notably through the design and production of national mineral prospectuses. A current example is the South American country of Guyana, where a model prospectus is being developed in close consultation with the Mines Commissioner. It will include background geographic and economic information on the country, details of the regulatory and fiscal environment, and descriptions of a number of selected regions favourable for gold and other deposits, with pertinent geologic and other data.



# 66. The Role of Geosciences in Development

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## ABSTRACT

Development needs to be measured not so much by indices or per capita rates as by the quality of life achieved by the majority of the people, in terms of housing, communication, energy and food supplies, tools of everyday living, safety of settlement sites, mitigation of risks from natural hazards, and other factors. The geosciences are involved, directly or indirectly, in many of these facets of development.

Exploitation of minerals for export, particularly metals and energy minerals, should no longer be accepted as a major role of the geosciences or as a measure of development in the developing countries. If geoscientists in those countries are to play a vital role in the development process, they should be increasingly involved in a wide spectrum of activities, such as:

1. industrial rocks and minerals for local processing and manufacturing for use within their own countries
2. exploration for and management of groundwater resources, especially in crystalline rock terrains in semi-arid regions
3. relationships between soil chemistry, water chemistry and environmental pollution, and public health
4. agropetrology, or the direct application of suitable minerals for increasing soil fertility
5. the geoscientific problems of urban geology
6. the cause of earthshakes and the delineation of unstable slopes
7. the evaluation of risks and natural hazards
8. dam-site and reservoir investigations and their effects on the environment
9. the preparation of environmental map atlases of natural regions like river valleys and coastal zones, and the constant monitoring of such regions

The Geosciences should, therefore, be directly involved in raising the standard of living of the people wherever possible, particularly in the developing countries.

## THE MEANING OF DEVELOPMENT

The word 'development' is one that has become very common in the language of politics and socio-economic affairs, and it has, in the past few decades, been bandied about without much concern for

definition. It therefore behoves us to define the term before we can proceed to discuss the subject of this address.

Of the many definitions of "development" that are found in the dictionaries, those that suit our context best are "growth" (Concise Oxford Dictionary) and "to make available or usable (its resources)" (Chambers Dictionary); and by 'resources' must be meant both natural and human resources.

But if development means growth, one may well ask "growth of what?" Is it economic growth, political growth, or social growth? If we mean economic growth in a broad sense, how do we measure such growth? Is it growth of per capita income, Gross National Product, birth rate, or infant mortality rate? Or do we make use of alphabetical indices such as POLI to measure growth?

To me, personally, none of these is satisfactory either as definitions or measures of development. If it means anything at all, the word development must surely imply a continuous raising of the standard of living of the majority of the people — or to use a more "in" phrase "improving the quality of life" of the people. There are no per capita rates or alphabetical indices that can measure this. We can only judge whether or not development has taken place by, among other factors, the standard of housing reached, the availability of good domestic water supplies, the sufficiency of food supplies, the absence of starvation and poverty, the supply of cheap energy, the safety of settlements, buildings and slopes, the condition of public health, the minimization of risks from natural hazards like earthquakes and volcanoes, the conservation of the environment, and the local processing and use of mineral and other natural resources within the country of origin. These are some of the more important factors that affect the quality of life, and the geosciences are, directly or indirectly, involved in many of them.

## MINERAL EXPLORATION AND EXPLOITATION

The mining industry has, in the past, had an important influence on the historical evolution of the geological sciences, and a major aspect of geoscientific education and activity has been the search for minerals, especially metals and energy minerals. These are the props of our present civilization, and they are likely to be so for decades to come. As a result, geoscientific activity in the developing countries was, and generally still is, mainly concerned with mineral exploration and the export of metals such as iron,

copper, and tin, and of oil to feed the demands of the industrialized nations. It is said that over 80 percent of the world's mineral resources are used by these countries, with only 25 percent of the world's population!

However, this dependence on export-oriented mining industries has had disastrous results in recent years, as can be seen in the present economic situations of Zambia, Nigeria, Malaysia, and the oil-exporting countries. It is time, therefore, to take stock, and to ask ourselves whether the underlying philosophy is still valid, and whether the search for and extraction of economic minerals should be our primary and our main concern.

I make bold to say that it is not, and I hope that I may be forgiven if I say this to a body of geoscientists whose concern is the search for minerals. However, the search for minerals must remain an important concern for the geoscientist, and especially the search for the industrial rocks and minerals, the utilization of which is a greater index of the development of a country than most other indices. By this I mean that the local exploitation of, for example, limestone for cement, quartz sands for glassware, kaolin for high-quality ceramic ware, clays for bricks and tiles, and phosphate for fertilizer, does more to raise the standard of living of the majority of the people of a developing country than the export of large quantities of a single mineral. Exportable minerals do bring in much needed foreign exchange, but this foreign exchange is often spent on non-essential luxury items, and the gap between rich and poor in such developing countries continues to grow.

Mineral exploration, if it is to contribute to development in the true sense of the word, should change its emphasis to:

1. the search for and evaluation of industrial rocks and minerals and their use within the country
2. the assessment of a country's metallic mineral resources and the conservation of such non-renewable wealth rather than unlimited and uncontrolled export
3. exploration of sea-bed resources
4. intensive search for alternative sources of energy

Furthermore, the role of the geosciences in the future should be increasingly engaged in a much wider spectrum of activities, all of which are essential for true development. These include:

1. the search for groundwater
2. the maintenance of public health
3. the improvement of soils
4. the safeguarding of urban growth
5. minimization of natural hazard risks
6. applications of geotechnical engineering

7. protection and monitoring of the environment
8. earth science education

## FUTURE ROLE OF GEOSCIENCES

### GROUNDWATER

In many parts of the world, particularly in the arid and semi-arid regions, exploration for groundwater is a priority activity of governments. Two examples may be quoted here. In the deserts of northern Africa, groundwater exploration takes the form of the search for fossil groundwater, generally hundreds of metres below the surface (e.g. 50 to 1 200 m in Saudi Arabia). Although the provision of this fossil water has resulted in tremendous socio-economic development of the desert regions (e.g. 500 productive wells and cultivation of 50 000 ha in the Sarte region of Libya), the supplies are non-renewable and over-extraction may have serious consequences (Margat and Saad 1984).

In the crystalline rock region of northern and southeastern Sri Lanka, where groundwater was previously thought to exist haphazardly only in pockets in the weathered overburden, nearly 5000 tube wells have been successfully located between 1978 and 1986 by searching for joints and fractures in the rocks. The provision of such water supplies has had important benefits, not only in Sri Lanka, but elsewhere in the world. These are: the reduction in time spent (five hours or more) by women in fetching water from great distances, increase of water consumption leading to greater personal and domestic cleanliness, and reduction in the incidence of water-borne diseases.

Both these developments have been made possible by the use of modern, sophisticated geoscientific techniques such as geophysical methods, landat imagery, and lineament interpretation. Several of the papers presented at this conference are ample proof of the role of geophysics in the search for water.

### ENVIRONMENTAL GEOCHEMISTRY AND MEDICO-GEOLOGY

There are many facets of the relationship between the environment and the community; the geosciences are involved in nearly all of these. This is particularly true of the geochemical aspects of the environment.

Pollution of the environment by industrial waste used to be considered a problem facing only industrialized nations, but this is now appearing more frequently in the developing countries. Bowel diseases in rural areas are rampant in those countries and are due mostly to such things as contamination of groundwater by animal and human fecal matter and high nitrate contents due to intensive fertilizer use. Rivers, streams, canals, and lakes are also becoming sewers for the disposal of industrial, animal and human waste, and of toxic substances such as pesticides and chemical fertilizers.

In the field of medico-geology, workers in Sri Lanka have found that: dental diseases are directly related to concentrations of flouride in soils and water; the hardness of water may affect the incidence of heart diseases; trace elements in the environment may relate to the occurrence of cancer (see Dissanayake 1983); and lung diseases such as pneumoconiosis are prevalent in cement factories and graphite mines in Sri Lanka.

Geochemistry has a vital role to play in all these areas of environmental pollution and medico-geology in tracing the cause-and-effect relationship and in monitoring those relationships over the years. Such studies are of prime importance for the health of the nation.

In Sri Lanka, the publication of a hydro-geochemical atlas (Dissanayake 1987), the preparation of a soil chemistry atlas, and studies of environmental pollution and health are important first steps in this area of geosciences and development.

#### AGROGEOLOGY

This is a comparatively new area of geoscientific activity, but it is one that assumes real importance when it is realized that the intensive use of chemical fertilizers may, in the long term, do more harm than good.

There are many who now think that it is very necessary to find alternatives to chemical fertilizers and to identify local rock materials that can be applied directly to the soil for various effects. Some of these effects are to correct acidity or alkalinity, to improve soil structure and fertility, to enhance resistance to soil erosion, and to help cut down water losses. Among the materials being used are limestone, dolomite, rock phosphates, volcanic scoria and zeolite-bearing rocks, all of which have considerable potential in these respects. Studies are being undertaken on some aspects of agrogeology, particularly in Africa, where Canadian expertise is involved; and in June 1986, the first African Conference on Agrogeology was held in Malawi. Relatively simple techniques such as the addition of peat, are now being developed in India, Canada, and the USA for making phosphatic rocks more selective without energy-intensive industrial processing (Chesworth and van Straaten 1986; Toomey 1987; Anonymous 1987a).

In Sri Lanka, a large apatite deposit, with proven reserves of 25 to 40 million metric tons is now being worked, the powdered apatite being applied to tea, rubber, and coconut lands for its long-term effects. Studies on converting the apatite into a water-soluble super phosphate have been carried out, and what is now needed is a pilot plant to test the process that has been evolved. However, it would be desirable for continued efforts to be made to resolve the problems of using this valuable resource with a minimum of chemical treatment.

#### URBAN GEOLOGY

It has been said that urbanization "is by far the most important social transformation of our times" and that by the end of the century, the urban population will be four times what it was in 1950. Moreover, most of the growth will be in the Third World countries. This rapid rate of urbanization, generally haphazard and uncontrolled in the developing countries, brings with it serious problems of development and planning. Many of the problems associated with urbanization are related to geological factors and are, therefore, the concern of the geoscientist. For example, over-extraction of groundwater by the urban population of Bangkok has led to subsidence in some parts of that city, with alarming consequences; and population pressure in Hong Kong has led to intensive construction on unsuitable slopes, leading to earthslips and related phenomena. Realizing that these are important problems for developing countries, the Association of Geoscientists for International Development (AGID) has now initiated three LANDPLAN conferences, in Bangkok, Kuala Lumpur, and Hong Kong, in order to draw attention to the role of geological factors in urbanization. The LANDPLAN IV is now in the planning stage; it hopes to bring together civil engineers, architects, geoscientists and town planners to look at the common problems of urbanization.

The point to be made here is that it is not enough to seek solutions after the problem has arisen; very often, it is too late for any permanent solutions to be found. It is necessary, rather, to monitor growth and development, especially of smaller towns and cities, before they become megalopolis, and this can be done by the preparation of earth-science maps for development and planning, for land-use management, for prevention or minimization of natural hazard damage, and other aspects of urbanization. The absence of such maps can lead to urban damage and losses through landslides, floods, and land subsidence; loss of mineral, water, and agricultural resources by building over land; increase of man-made and man-aided geological hazards such as collapse of slopes due to excavation for construction; contamination of ground and surface waters through improper waste disposal and landfill; and coastal erosion due to lack of supply of sand by sand-extraction from the river beds.

For many towns and cities, the basic information is available from a number of scattered sources. The need is to put this data together, collect data where gaps exist, plot the data and prepare the maps of landforms, geology and resources, land use, hydrology, slopes, waste disposal, groundwater and environmental contamination and pollution, and city expansion. The expense involved need not be very great, as the preparation of these maps could form suitable research projects for geoscience post-graduate students working in collaboration with local authorities.

As an example of what is available, but is not generally known, one could quote an expert from UN-ESCAP who, when engaged in studying the urban geology of Colombo's satellite town, Sri Jayawardenapura, found that there were over 200 boreholes drilled in the city of Colombo, the data from which, when put together, would give him a good idea of the subsurface conditions in the city.

Urban geology and regional environmental geology (see below) are relatively new areas of geoscientific involvement, but they need to be developed in the future, if the quality of life of people is to be improved.

### RISKS FROM NATURAL HAZARDS

In many parts of the world, loss of life and damage to property through earthquakes, volcanic eruptions, earthshakes, and soil and coastal erosion are very real and very considerable. Some of these hazards are due to natural causes beyond human control, but others are largely due to human practices. All of them require the attention of the geosciences.

Earthquakes and volcanoes are hazards about which we can do little, except to try and understand their causes, learn to recognize signs of their imminence, and devise methods of prediction in order to minimize damage and loss of life. Research and training in these areas are proceeding. For example, AGID recently sponsored the first International Symposium on Neotectonics and Volcanic Risks which was held in Bogota, in December 1986, and was attended by 150 geoscientists mainly from 14 Latin American countries. Seismology and earthquake engineering studies are being vigorously pursued in Mexico, Central America, and South America.

Desertification, soil and coastal erosion, and earthshakes are very much accelerated and assisted by such human activities as deforestation and removal of vegetation, overgrazing of marginal lands, intensive cultivation of unsuitable slopes, poor drainage of unconsolidated scree slopes, and removal of material from coastal strips.

Earthshakes, for example, are a common hazard in tropical lands, affecting roads and communications, settlements, terraced fields, and cultivated and built-up slopes. Geoscientists are now increasingly involved in remedial and preventative measures, and also in monitoring unstable slopes in order to understand the nature of the movements and their causes and effects.

Coastal erosion is a serious problem in many tropical countries such as Sri Lanka, where the problem is aggravated by beach- and river-sand mining, and the removal of coral for lime burning. In 1984, for example more than 18 000 tons of

coral were collected from the south-western coastal area of Sri Lanka, and approximately 500 000 "cubes" of sand were mined from the western and southern coasts. It has been estimated that about 175 000 to 285 000 cubic metres of coastal sand are lost to erosion each year along the western and southern coasts of the island (a length of 685 km long segment running north from Colombo (Anonymous 1987b)).

In all areas of natural hazards, effective action is necessary by teams of scientists and engineers. Geoscientists are contributing their understanding of geological conditions to problem-solving and preventative action.

### GEOTECHNICAL ENGINEERING

It was not so long ago that geologists were hardly ever consulted when dams were to be built or tunnels constructed. If they were, it was only when problems arose from the presence of inconvenient geological structures such as faults and joints, from excessive seepage, and from similar geological conditions. Such, for example, was the case during the siting of the Kotmale Dam and during the drilling of the Polgolla tunnel in Sri Lanka (Vitanage 1982). Fortunately, for everyone concerned, and for the good of the country, that stage has been passed, and we now have a relatively new class of geoscientists known as "geotechnical engineers" who are very much involved in these activities from the very beginning.

Engineering geologists (geotechnical engineers) are now attached to all major dam construction projects from the very beginning. Not only do they carry out detailed geological mapping of the site, but also monitor it during and even after construction has been completed. In a recent visit to Randenigala-Rantembe, the last of a series of dams and reservoirs on Sri Lanka's longest river, the Mahaweli Ganga, I was very impressed by the meticulous and detailed mapping of the dam sites, the grouting tunnel and the environments, carried out by the young Sri Lankan geotechnical engineers attached to the scheme.

### ENVIRONMENTAL MONITORING

Development projects in various parts of the world are generally regional in scope, and are sometimes confined to natural regions such as river valleys and basins or coastal belts. The Mahaweli Development scheme in Sri Lanka is one such scheme, involving the building of a succession of dams along the river for hydro-electric purposes, and the diversion of water for irrigation. As a result, changes such as reservoir silting, micro-seismic activity, slope instability, salination of irrigated land, and displacement of population are taking place in the valley. These effects are influencing the social and physical pattern



of the land, but we know little or nothing of how and to what extent¹.

Monitoring the effects is a very necessary adjunct of all development programs, and we can do this by following the examples of the United States Geological Survey and the Bureau of Economic Geology of the University of Texas in preparing Environmental Map atlases, needing multidisciplinary effort. These would present a record of the existing state of the different environments within the region and the processes going on in them. Each atlas would, for example, contain maps of the geology, mines, and minerals, landforms and substrate conditions, land-use patterns, erosion, sedimentation, rainfall, stream discharge, water systems, slopes and slope stability, and geochemistry of soils and waters. Atlases would also provide the means of communication between, and sources of information for, the many people involved in one way or another in the life of the region.

However, the embarking on such a venture requires, besides considerable financial expenditure, the appreciation of the benefits of such activity. Such appreciation and understanding is generally only present when immediate and concrete benefits are implemented. So we, in the developing countries, may have to wait a very long time before the long-term benefits of such monitoring of the environment are recognized and appropriate action taken to establish the kind of monitoring system described above.

## CONCLUSIONS

### EARTH SCIENCE EDUCATION

We have so far been dealing with an area of activity in which the geosciences have to be, and are directly involved. There is another side to this activity, where the involvement is indirect. This is the field of earth-science education at all levels, secondary, tertiary, and adult. As I have said elsewhere (Cooray 1988), we geoscientists have been too reluctant to talk to the non-specialist about our science, too backward in pointing out how our disciplines affect the community at so many points perhaps even to being unaware of the importance of geoscientific factors that influence the environment.

Probably one of the most important needs of our time is to make the people around us realize the vital necessity of the careful use of resources and for the preservation and conservation of the environment. This is not an easy task, given the basic selfishness of

man and his innate desire to get rich by the quickest possible means, very often irrespective of the interests of others or of the legalities of his actions. But it is a task we must address ourselves to consciously and at all levels.

Although earth science is taught in many schools in North America and Europe, this is not true for the developing countries. A start has been made, as in Thailand and Sri Lanka, to introduce integrated earth-science curricula into secondary schools. In Thailand, for example, AGID is now sponsoring a pilot scheme in a school where an earth-science curriculum is being tried out as part of the regular program. In Sri Lanka, some aspects of earth science are now being taught in school years 6 to 11 in the two compulsory subjects "Science" and "Social Studies", but there are serious gaps in the curricula of the two. Again, AGID and the Curriculum Development Committee of the Department of Education are holding a series of meetings in which the gaps have been identified and suggestions made as to how they should be filled. These discussions are still going on, and, hopefully, a more meaningful content of earth-science will be introduced into the secondary school program of the Sri Lankan schools sometime in the future.

At the tertiary level, we do need constant revision and reassessment of our teaching and research programs. A good foundation in 'pure' geology is, of course, a basic necessity, because as has been said by someone, "all exploration from pick and shovel to country-wide aerial surveying is based on someone's geological concept." The important thing is that this truism applies to all the aspects of applied geology - hydrogeology, engineering geology, agrogeology, medico-geology, and environmental geology. Without proper basic geological concepts, we may make serious mistakes, whatever the area of activity. Basic geological training is only a prerequisite for the increased production of applied earth scientists within our own borders and familiar with local conditions. This is the direction which tertiary education at both undergraduate and post-graduate levels must take in the future. Other neglected areas which are necessary for development are modern structural geology, Quaternary geology, and marine geology. This neglect should be remedied if we are to keep pace with evolving concepts in the geosciences.

Last, but certainly not least, the need to educate and inform the general public about the geosciences in terms understandable to the layman and using whatever means we can, is a necessity. It is only by this means that we can show them how our science is relevant to everyday living, how it can raise the standard of living and improve the quality of their lives. We must demonstrate to them the totality of the resources of the land, and impress upon them the necessity of using those resources wisely and well for

1. It might be noted that the Canadian-Sri Lanka Colombo Plan survey of the Mahavelle Ganga basin published a report in 1962 which included geological maps, maps of soils and forestry, and land use and engineering assessments for the development of the hydro-electric potential.

the benefit not only of their children, but also for the benefit of generations to come.

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# **Modern Computer-Based Methodologies: Their Coming Role in Exploration**

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# 67. The Relevance of Data Base Technology to Resource Exploration Data

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## ABSTRACT

Over the last ten years, substantial advances have been made in the field of data base technology—the most evident being the appearance of practical and efficient Relational data base management systems (DBMS). These advances have clearly benefitted geochemical exploration but geophysical exploration, which produces the largest volumes of mineral exploration data, has gained little. One reason for this is that modern DBMSs were developed principally for business and administrative data processing. Geophysical data structures and processes are sufficiently different to make a commercial DBMS inapplicable.

The fundamental concepts and basic techniques of data base technology are, however, highly relevant to geophysical data and if properly adapted can confer substantial benefits. The techniques of data-independence could greatly improve efficiency in the transfer of data between the acquisition and processing environments and between different organizations, and also improve the efficiency of processing systems in general. In the longer term, development of data management systems based on more appropriate models should be the first priority.

## INTRODUCTION

Of the forty-four papers in the proceedings of Exploration '77, there are only two specifically on the subject of computer applications, and only one of these (Howarth and Martin 1977) makes a (brief) reference to data base techniques. Since Exploration '77, substantial advances have been made in geophysical and geochemical exploration technology. A large proportion was made possible by advances in computer technology—the most evident being the advent of the microprocessor and solid state memory chip. Over the same period, there have also been substantial advances in data base technology, the most evident being the appearance of practical and efficient Relational data base management systems (DBMS). It was an omen that Howarth and Martin's mention of the data base technique was in the context of geochemistry, as this is the exploration discipline that has since benefitted the most from DBMS advances. Geophysical exploration, though it creates far larger volumes of digital data, has scarcely benefitted. This paper examines the reasons for this and describes the benefits of data base technology

that are most relevant to, and should be actively pursued by practitioners of, resource exploration.

## DATA BASE TECHNOLOGY AND THE DBMS

Data base technology studies the properties of data bases, the problems of creating and managing them, and the human, hardware, and software solutions to these problems. Its principal objective is to improve the efficiency of the storage and retrieval of large volumes of digital data—especially where many different but related types of data are stored in the same data base. Data base technology is not concerned with what the data "means", this is the concern of "Applications" programs.

Martin (1975) defines a data base as follows:

"A data base may be defined as a collection of interrelated data stored together without harmful or unnecessary redundancy to serve one or more applications in an optimal fashion: the data are stored so that they are independent of programs which use the data; a common and controlled approach is used in adding new data and in modifying and retrieving existing data within the data base."

Many people use the terms "data base" and "DBMS" interchangeably, a habit which reduces clarity in an already adequately obscure area. A DBMS is simply a chosen set of solutions to specific problems, wrapped in a software package. The relationship between the data base and the DBMS is described by Olle (1976) as:

"A data base is a set of data stored in some special way in direct access computer storage. A DBMS is the software that handles the storage and retrieval of the records in this data base."

## DATA BASE STRUCTURES

Different types of DBMS are categorized by the underlying structural model that is used for the data base. The three principal structural models are:

1. "Hierarchical" systems, which permit one-to-many linkages between data items in a tree structure.
2. "Network" systems which permit many-to-many linkages in a network structure.
3. "Relational" systems, which (theoretically) reject predetermined linkages and treat the data as sets of tables.

A comprehensive description and comparison of these three categories of DBMS is given in Data

(1982) and Martin (1975). The mathematical bases of the data structures are described by Berstins (1975). As a practical illustration of the differences between these data structures, let us consider a simple case of lithochemical data management.

Each sample is analyzed for a suite of elements, has a unique sample number, and is also labeled by survey area and rock type. The data arrives in no particular order as analysis results in batches. Each batch records a sample number, the area and rock type, and a list of results for the various elements. If these records were stored in ascending order of sample number, we could quickly find any individual record given its sample number. But if we wanted to find all samples in granites we would have to scan the entire file. Therefore retrieval is inefficient except for a single and unlikely requirement (like having a telephone directory ordered by telephone number). Furthermore, specific values of area and rock type would be repeated thousands of times. Hence storage is inefficient also. So how can we structure this data for greater efficiency of storage and retrieval?

One way would be to create a hierarchical structure (Figure 67.1). We group the data by area, then by rock type within each area, then by element within each rock type. A three-level index allows rapid access to any result. To find "all analyses for Cu in granites in the Kowichan area" is now simple. Inverse questions, however, such as "find all samples with Pb greater than 100 ppm" are just as difficult to answer as before, i.e. they still require a search through every bundle.

A network structure (Figure 67.2) could make alternative search paths equally efficient. We can

store the analysis results alone in order of magnitude and create separate indexes (sets of "pointers") from the unique values of area, rock type, element, and sample number. To "find all samples with Pb greater than 100 ppm" we can now go directly from the element index to all the Pb samples instead of via area and rock type. We can answer compound questions by simple boolean operations, e.g. to find all Pb results from granites, we get the set of all pointers to granite from the rock index and find its intersection with the set of all Pb results from the element index. Note that each rock type, element name, and sample number appears only once. It seems, therefore, that we have optimized both storage and retrieval. Note also though, that four pointers converge on each result item, one pointer each from specific values of area, rock, element, and sample number. Pointers have to be expressed as numbers and stored somewhere just like the data itself.

Consider ten areas each with ten rock types. Ten samples were taken in each area/rock type and each sample analyzed for ten elements. The bottom levels of both the hierarchy and network will each contain 10 000 analysis results. The former has 1000 pointers to it though, whilst the latter has 40 000. Counting pointers as well as data items, the network is over twice the size of the hierarchy, even though the hierarchy has many replicated data items. As the number and variety of data items increases, the size of the network data base grows exponentially. Eventually, it becomes necessary to remove all but the two or three most used access paths.

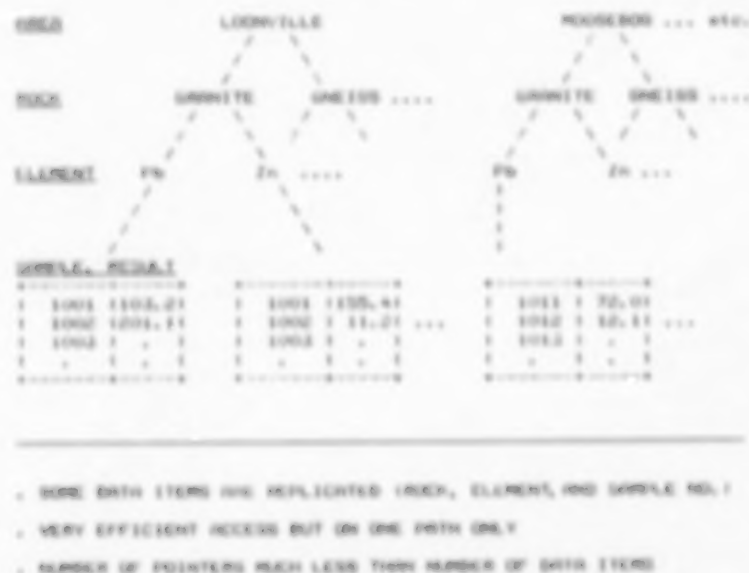


Figure 67.1. Geochemical data in a hierarchical structure.



Figure 67.2. Geochemical data in a network structure.

THE DATA IS PUT INTO TWO RELATIONS (TABLES) SO:-							
1) SAMPLE_ROCK_AREA				2) SAMPLE_ELEMENT_RESULT			
S	LOC	ROCK	AREA	S	LOC	EL	RES
1	1001	GRANITE	LIVER	1	1001	Pb	1.17
1	1002	GRANITE	LIVER	1	1001	Zn	0.02
1	1003	GRANITE	LIVER	1	1001	Cu	0.0
1	1004	GRANITE	LIVER	1	1002	Pb	0.0
1	1005	GRANITE	LIVER	1	1002	Zn	0.02
1	1006	GRANITE	LIVER	1	1002	Cu	0.0
1	1007	GRANITE	LIVER	1	1003	Pb	0.0
1	1008	GRANITE	LIVER	1	1003	Zn	0.0
1	1009	GRANITE	LIVER	1	1003	Cu	0.0
1	1010	GRANITE	LIVER	1	1004	Pb	0.0
1	1011	GRANITE	LIVER	1	1004	Zn	0.0
1	1012	GRANITE	LIVER	1	1004	Cu	0.0
1	1013	GRANITE	LIVER	1	1005	Pb	0.0
1	1014	GRANITE	LIVER	1	1005	Zn	0.0
1	1015	GRANITE	LIVER	1	1005	Cu	0.0
1	1016	GRANITE	LIVER	1	1006	Pb	0.0
1	1017	GRANITE	LIVER	1	1006	Zn	0.0
1	1018	GRANITE	LIVER	1	1006	Cu	0.0
1	1019	GRANITE	LIVER	1	1007	Pb	0.0
1	1020	GRANITE	LIVER	1	1007	Zn	0.0
1	1021	GRANITE	LIVER	1	1007	Cu	0.0
1	1022	GRANITE	LIVER	1	1008	Pb	0.0
1	1023	GRANITE	LIVER	1	1008	Zn	0.0
1	1024	GRANITE	LIVER	1	1008	Cu	0.0
1	1025	GRANITE	LIVER	1	1009	Pb	0.0
1	1026	GRANITE	LIVER	1	1009	Zn	0.0
1	1027	GRANITE	LIVER	1	1009	Cu	0.0
1	1028	GRANITE	LIVER	1	1010	Pb	0.0
1	1029	GRANITE	LIVER	1	1010	Zn	0.0
1	1030	GRANITE	LIVER	1	1010	Cu	0.0
1	1031	GRANITE	LIVER	1	1011	Pb	0.0
1	1032	GRANITE	LIVER	1	1011	Zn	0.0
1	1033	GRANITE	LIVER	1	1011	Cu	0.0
1	1034	GRANITE	LIVER	1	1012	Pb	0.0
1	1035	GRANITE	LIVER	1	1012	Zn	0.0
1	1036	GRANITE	LIVER	1	1012	Cu	0.0
1	1037	GRANITE	LIVER	1	1013	Pb	0.0
1	1038	GRANITE	LIVER	1	1013	Zn	0.0
1	1039	GRANITE	LIVER	1	1013	Cu	0.0
1	1040	GRANITE	LIVER	1	1014	Pb	0.0
1	1041	GRANITE	LIVER	1	1014	Zn	0.0
1	1042	GRANITE	LIVER	1	1014	Cu	0.0
1	1043	GRANITE	LIVER	1	1015	Pb	0.0
1	1044	GRANITE	LIVER	1	1015	Zn	0.0
1	1045	GRANITE	LIVER	1	1015	Cu	0.0
1	1046	GRANITE	LIVER	1	1016	Pb	0.0
1	1047	GRANITE	LIVER	1	1016	Zn	0.0
1	1048	GRANITE	LIVER	1	1016	Cu	0.0
1	1049	GRANITE	LIVER	1	1017	Pb	0.0
1	1050	GRANITE	LIVER	1	1017	Zn	0.0
1	1051	GRANITE	LIVER	1	1017	Cu	0.0
1	1052	GRANITE	LIVER	1	1018	Pb	0.0
1	1053	GRANITE	LIVER	1	1018	Zn	0.0
1	1054	GRANITE	LIVER	1	1018	Cu	0.0
1	1055	GRANITE	LIVER	1	1019	Pb	0.0
1	1056	GRANITE	LIVER	1	1019	Zn	0.0
1	1057	GRANITE	LIVER	1	1019	Cu	0.0
1	1058	GRANITE	LIVER	1	1020	Pb	0.0
1	1059	GRANITE	LIVER	1	1020	Zn	0.0
1	1060	GRANITE	LIVER	1	1020	Cu	0.0
1	1061	GRANITE	LIVER	1	1021	Pb	0.0
1	1062	GRANITE	LIVER	1	1021	Zn	0.0
1	1063	GRANITE	LIVER	1	1021	Cu	0.0
1	1064	GRANITE	LIVER	1	1022	Pb	0.0
1	1065	GRANITE	LIVER	1	1022	Zn	0.0
1	1066	GRANITE	LIVER	1	1022	Cu	0.0
1	1067	GRANITE	LIVER	1	1023	Pb	0.0
1	1068	GRANITE	LIVER	1	1023	Zn	0.0
1	1069	GRANITE	LIVER	1	1023	Cu	0.0
1	1070	GRANITE	LIVER	1	1024	Pb	0.0
1	1071	GRANITE	LIVER	1	1024	Zn	0.0
1	1072	GRANITE	LIVER	1	1024	Cu	0.0
1	1073	GRANITE	LIVER	1	1025	Pb	0.0
1	1074	GRANITE	LIVER	1	1025	Zn	0.0
1	1075	GRANITE	LIVER	1	1025	Cu	0.0
1	1076	GRANITE	LIVER	1	1026	Pb	0.0
1	1077	GRANITE	LIVER	1	1026	Zn	0.0
1	1078	GRANITE	LIVER	1	1026	Cu	0.0
1	1079	GRANITE	LIVER	1	1027	Pb	0.0
1	1080	GRANITE	LIVER	1	1027	Zn	0.0
1	1081	GRANITE	LIVER	1	1027	Cu	0.0
1	1082	GRANITE	LIVER	1	1028	Pb	0.0
1	1083	GRANITE	LIVER	1	1028	Zn	0.0
1	1084	GRANITE	LIVER	1	1028	Cu	0.0
1	1085	GRANITE	LIVER	1	1029	Pb	0.0
1	1086	GRANITE	LIVER	1	1029	Zn	0.0
1	1087	GRANITE	LIVER	1	1029	Cu	0.0
1	1088	GRANITE	LIVER	1	1030	Pb	0.0
1	1089	GRANITE	LIVER	1	1030	Zn	0.0
1	1090	GRANITE	LIVER	1	1030	Cu	0.0
1	1091	GRANITE	LIVER	1	1031	Pb	0.0
1	1092	GRANITE	LIVER	1	1031	Zn	0.0
1	1093	GRANITE	LIVER	1	1031	Cu	0.0
1	1094	GRANITE	LIVER	1	1032	Pb	0.0
1	1095	GRANITE	LIVER	1	1032	Zn	0.0
1	1096	GRANITE	LIVER	1	1032	Cu	0.0
1	1097	GRANITE	LIVER	1	1033	Pb	0.0
1	1098	GRANITE	LIVER	1	1033	Zn	0.0
1	1099	GRANITE	LIVER	1	1033	Cu	0.0
1	1100	GRANITE	LIVER	1	1034	Pb	0.0
1	1101	GRANITE	LIVER	1	1034	Zn	0.0
1	1102	GRANITE	LIVER	1	1034	Cu	0.0
1	1103	GRANITE	LIVER	1	1035	Pb	0.0
1	1104	GRANITE	LIVER	1	1035	Zn	0.0
1	1105	GRANITE	LIVER	1	1035	Cu	0.0
1	1106	GRANITE	LIVER	1	1036	Pb	0.0
1	1107	GRANITE	LIVER	1	1036	Zn	0.0
1	1108	GRANITE	LIVER	1	1036	Cu	0.0
1	1109	GRANITE	LIVER	1	1037	Pb	0.0
1	1110	GRANITE	LIVER	1	1037	Zn	0.0
1	1111	GRANITE	LIVER	1	1037	Cu	0.0
1	1112	GRANITE	LIVER	1	1038	Pb	0.0
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1	1114	GRANITE	LIVER	1	1038	Cu	0.0
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1	1121	GRANITE	LIVER	1	1041	Pb	0.0
1	1122	GRANITE	LIVER	1	1041	Zn	0.0
1	1123	GRANITE	LIVER	1	1041	Cu	0.0
1	1124	GRANITE	LIVER	1	1042	Pb	0.0
1	1125	GRANITE	LIVER	1	1042	Zn	0.0
1	1126	GRANITE	LIVER	1	1042	Cu	0.0
1	1127	GRANITE	LIVER	1	1043	Pb	0.0
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1	1129	GRANITE	LIVER	1	1043	Cu	0.0
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1	1131	GRANITE	LIVER	1	1044	Zn	0.0
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1	1133	GRANITE	LIVER	1	1045	Pb	0.0
1	1134	GRANITE	LIVER	1	1045	Zn	0.0
1	1135	GRANITE	LIVER	1	1045	Cu	0.0
1	1136	GRANITE	LIVER	1	1046	Pb	0.0
1	1137	GRANITE	LIVER	1	1046	Zn	0.0
1	1138	GRANITE	LIVER	1	1046	Cu	0.0
1	1139	GRANITE	LIVER	1	1047	Pb	0.0
1	1140	GRANITE	LIVER	1	1047	Zn	0.0
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1	1142	GRANITE	LIVER	1	1048	Pb	0.0
1	1143	GRANITE	LIVER	1	1048	Zn	0.0
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1	1146	GRANITE	LIVER	1	1049	Zn	0.0
1	1147	GRANITE	LIVER	1	1049	Cu	0.0
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1	1155	GRANITE	LIVER	1	1052	Zn	0.0
1	1156	GRANITE	LIVER	1	1052	Cu	0.0
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1	1175	GRANITE	LIVER	1	1059	Pb	0.0
1	1176	GRANITE	LIVER	1	1059	Zn	0.0
1	1177	GRANITE	LIVER	1	1059	Cu	0.0
1	1178	GRANITE	LIVER	1	1060	Pb	0.0
1	1179	GRANITE	LIVER	1	1060	Zn	0.0
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1	1181	GRANITE	LIVER	1	1061	Pb	0.0
1	1182	GRANITE	LIVER	1	1061	Zn	0.0
1	1183	GRANITE	LIVER	1	1061	Cu	0.0
1	1184	GRANITE	LIVER	1	1062	Pb	0.0
1	1185	GRANITE	LIVER	1	1062	Zn	0.0
1	1186	GRANITE	LIVER	1	1062	Cu	0.0
1	1187	GRANITE	LIVER	1	1063	Pb	0.0
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1	1190	GRANITE	LIVER	1	1064	Pb	0.0
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1	1192	GRANITE	LIVER	1	1064	Cu	0.0
1	1193	GRANITE	LIVER	1	1065	Pb	0.0
1	1194	GRANITE	LIVER	1	1065	Zn	0.0
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1	1196	GRANITE	LIVER	1	1066	Pb	0.0
1	1197	GRANITE	LIVER	1	1066	Zn	0.0
1	1198	GRANITE	LIVER	1	1066	Cu	0.0



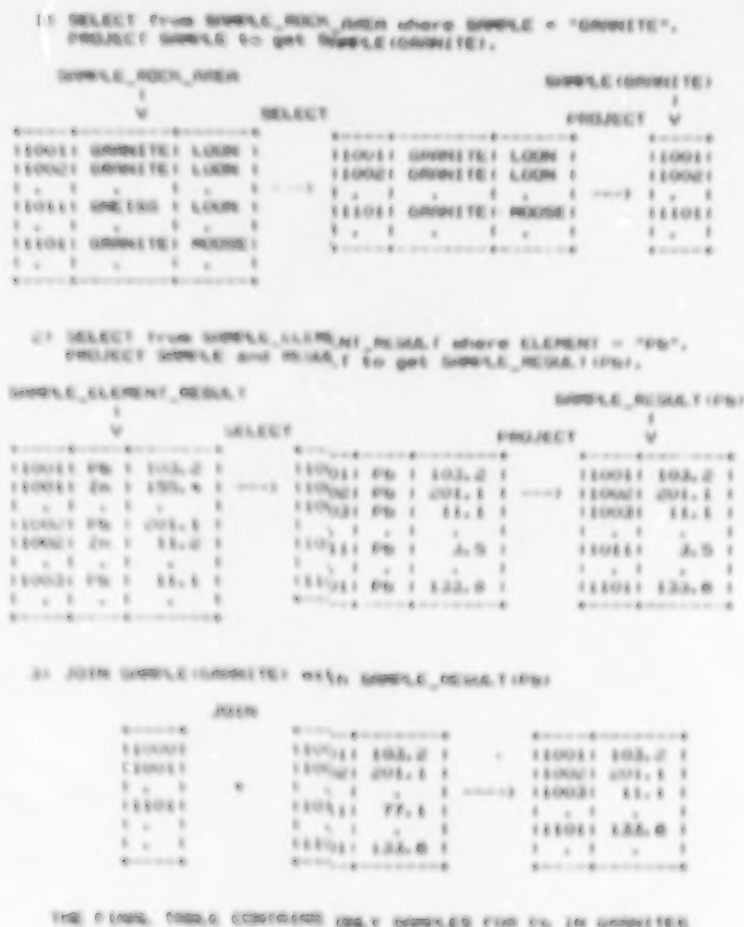


Figure 67.6. Relational operations on geochemical data to extract the subset "all results for Pb in granites".

two Relations SAMPLE ROCK AREA and SAMPLE ELEMENT RESULT. The key field(s) of each relation are indicated.

Relational theory shows that any desired subset of the data can be extracted by application of the three Relational operations PROJECT, SELECT, and JOIN. The first two, PROJECT and SELECT, extract specified columns and rows respectively from an individual table. JOIN combines two tables into a single one. To retrieve the subset "all samples from granites" would require the following sequence of operations:

1. SELECT from SAMPLE_ROCK_AREA where SAMPLE = "GRANITE". PROJECT SAMPLE to get SAMPLE (GRANITE).
2. SELECT from SAMPLE_ELEMENT_RESULT where ELEMENT = "Pb". PROJECT SAMPLE and RESULT to get SAMPLE_RESULT (Pb).
3. JOIN SAMPLE (GRANITE) with SAMPLE_RESULT (Pb)

Figure 67.4 illustrates the process. The final table contains all results for Pb in granites and only these results. Any definable subset can be extracted by similar sequences of operations (e.g. substituting "MOOSE" for "GRANITE" in operation 1 would allow the extraction of all Pb samples in the MOOSE area). The Relational structure, therefore, fulfills its promise. Any identifiable subset can be extracted with equal efficiency, and the data base does not grow exponentially as the number and variety of data items increases. There are still problems though. Although Relational data bases do not grow exponentially, they tend to start out much larger than in other structures, and equal efficiency of retrieval can mean "equally inefficient". With no preset pointers, all logical linkages between records must be established by key values "on the fly" as the operation proceeds, and must be re-established for every subsequent operation. Relational DBMS get around this problem by simply offering the user the capability to build indexes "if necessary". Neverthe-

less, the ability to view the data always simply as sets of tables, and to have a minimal set of formally defined operations to retrieve any subset is very advantageous to the user.

#### DATA STORAGE AND RETRIEVAL IN THE DBMS

The most visible and impressive advantage of the DBMS is in selective retrievals. A small subset of a large data base can be found and extracted in minutes or seconds. The Ontario Petroleum Data System (OPDS) of the Ontario Ministry of Natural Resources (Holroyd and Trevaill 1985) contained, in 1985, 60 Megabytes of data on over 30 000 oil and gas wells in Ontario, including over 250 000 stratigraphic records. The task -

"Find all wells in Moore township that intersect the Guelph formation, and extract the Guelph formation thickness."

- takes a few seconds to specify and a few more to execute. If the data were in simple files rather than in a structured data base, it would take over a hundred times longer to execute. This advantage is partially offset, however, by what appears to be a fundamental DBMS law - "retrieval efficiency is inversely proportional to storage efficiency" as noted above in the case of hierarchical versus network. The OPDS data base takes over twice the amount of disk space than the same data in simple files, and loading the data to the data base takes at least ten times longer than writing it to simple files.

"Data" has many levels. At the lowest level is the single data item or "field". Another name for field is "element" which indicates its nature, i.e. it cannot be decomposed into smaller components without loss of integrity. Fields are grouped into "Records". Records are grouped into "files" or "data sets". Data sets are grouped into data bases. These abstract terms can be made more tangible by saying that a field is a description of a single aspect of an object, a record is a description of a whole object, and a data set is a description of a set of objects all of the same type. A data base is more complicated. It can be a description of several sets of objects of different types, a description of a single set of objects from several different viewpoints, or a combination of both.

In a simple file, records are stored together with "sequential access". To access the 10th record, you simply read through the previous nine records in sequence. If you want records where the field "ROCK" contains the name "GRANITE", you read every record, and keep those containing this value. The next level of storage is the "direct access" file. Every record has its own storage "address". You can go directly to the Nth record without having to read through the preceding N-1.

In a data base, further levels of complexity are required. To find records directly by field content

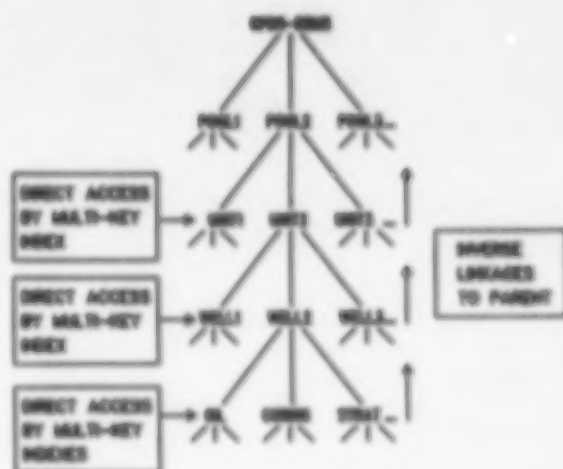


Figure 67.5. General structure of the OPDS data base.

requires both direct access and previously compiled pointers to specific content. One access method uses a separate index of content versus address. In the most efficient systems, even the index has an index like a library catalog. For example, the search would start with the O's, find OR's, then the ORA's, etc. Finally, "granite" would be found attached to a list of the addresses of all records containing this value. The list could be used to recover all these records, or as described in the case of the geochemical network, could be combined with other lists to refine the selection further. "Inverse linkages" can also be placed within the records themselves to further speed up the process. These are pointers back to the higher levels of the data base.

Figure 67.5 shows the general structure of the OPDS data base. It looks like a hierarchy but the indices and inverse linkages make it a network. The process to "Find all wells in Moore township that intersect the Guelph Formation" employs both an index and the inverse pointers. The index to the stratigraphy records is used to find all those for Guelph, then the inverse linkages back to Well are used to find if the well is in Moore township.

#### DATA INDEPENDENCE IN THE DBMS

A second, less visible, but no less important, advantage offered by the DBMS is "data independence". This means independence of the logical and physical structure of the data from the applications which access and process the data.

With the simple files generally used for geoscience data, group A gets a tape from group B, accompanied (if they are lucky) by a written description of the data structure and content. They then write a program to read the data. This program serves for all future tapes from group B, until they decide to change the data content and/or structure, at which time the program has to be changed ac-

cordingly. Then there are all the other different programs needed to read the data from groups C, E, and D... etc. The applications are clearly dependent on the logical and physical structure of the data. This creates substantial extra work and many problems. The DBMS aims to avoid these problems by maintaining data independence.

Figure 67.6 (from Date 1982) shows the conceptual architecture of a data base system, with the following levels:

- 1) (Top) The user-level access to the data base.
- 2) Several "External view": each one defines a subset of the data base relevant to a different user group.
- 3) The "Conceptual view": this is the complete logical description of the physical data base - a catalog of the types of data present.
- 4) "Storage", which consists of the actual data itself.

Note the "mapping" in the middle two levels. When users require data according to their external view, the system follows a map to find this data in the overall catalog, then follows a second map to find where the data is physically stored. These "maps" consist essentially of translation from one frame of reference to another. On successively lower levels, the frames of reference get more physical and specific and less logical and general. To illustrate

this, let us consider a geoscience survey data base containing geological, geochemical, and geophysical data. Figure 67.7 shows the view and mapping for a geochemistry user of this data base.

The key to data independence is that the maps are dynamic. The physical storage could be completely rearranged but the "conceptual view" would remain unchanged. Only the map between the two would change to redirect queries to the new addresses. Likewise, the conceptual view of the data base could also be changed without necessarily requiring changes to individual external views. An external view would only be forced to change if data types within it were deleted from the data base.

## EXPLORATION DATA CHARACTERISTICS

DBMS were originally developed to suit the structures and manipulation requirements of business and administration data. All DBMS commercially available today are direct descendants of these. The fact that DBMS are widely used for scientific purposes is largely coincidental, i.e. scientific information management needs are often similar to those of business. Systems explicitly described as "scientific" are generally standard DBMS with mathematical and statistical utilities grafted on. Exploration data, however, differs significantly from business data in both retrieval requirements and structure.

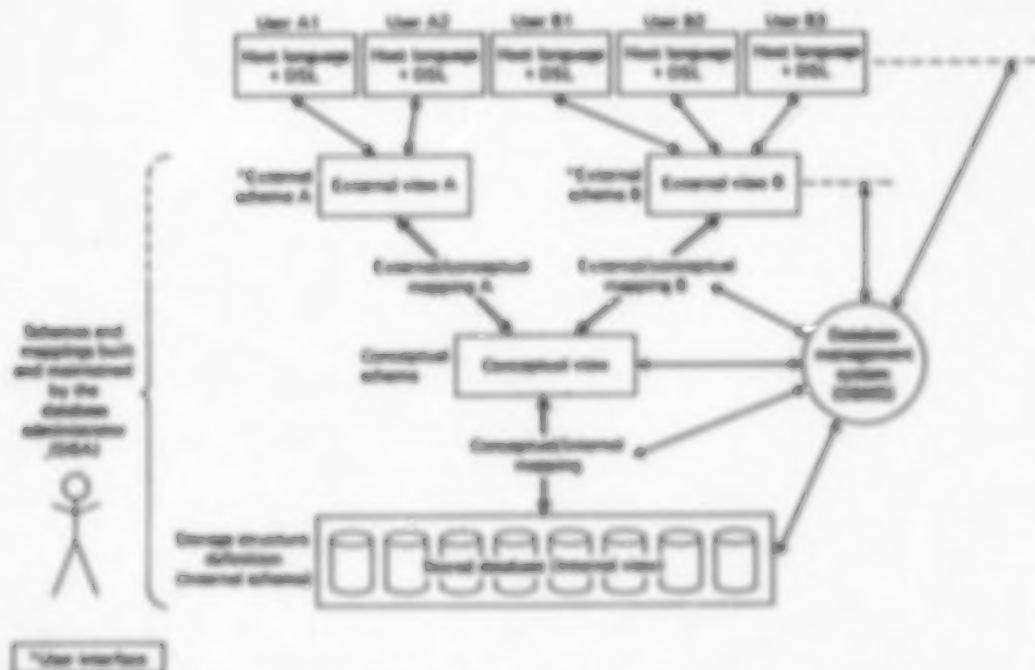


Figure 67.6. Data base system architecture (from Date 1982).

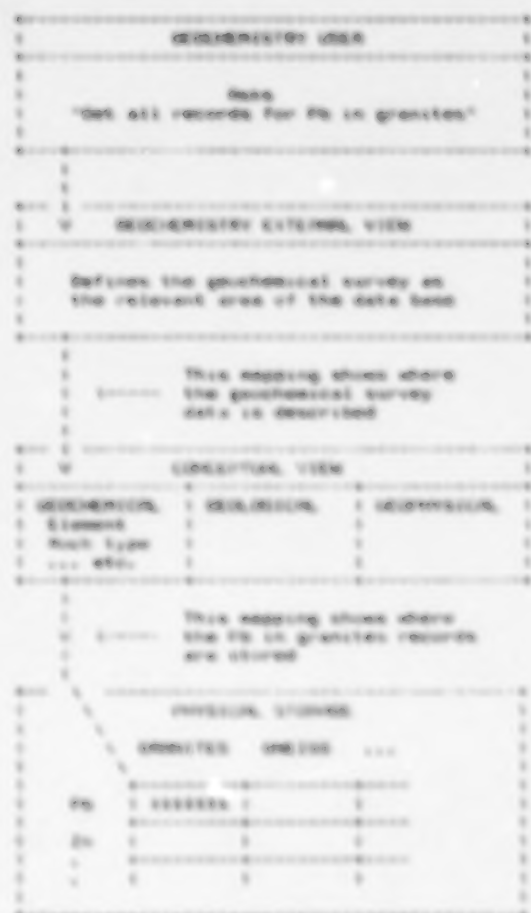


Figure 67.5. Views and mapping in a geoscience data base.

## EXPLORATION DATA RETRIEVAL REQUIREMENTS

Consider a data set in tabular form. Crain (1976) points out that business applications generally require individual rows (single occurrences of different data items) from the table, whereas scientific applications generally require columns (multiple occurrences of the same data item).

This is especially true of Exploration data. The largest aerogeophysical survey ever conducted, the Thailand survey (Geological Survey of Canada 1983), produced several gigabytes of data. Not once, during the enormously long and complex compilation processes applied, did the need arise to retrieve data by "row" (i.e. the magnetics, spectrometer, VLF, time, positional coordinates, etc., of a single measurement point). All retrievals were of very large "columns" of data - i.e. vectors. (G. Toed,

Vice President, Displaying Services, Toronto, personal communication, 1988)

The predominance of large volume columnar retrieval has a profound effect on the level of sophistication needed in the retrieval mechanisms. To illustrate this, consider a DBMS which could zero in on any individual record in a large data base after reading, on average, only ten index and "mapping" records to lead it to its target. This would be a very powerful system, with the concomitant disadvantages.

Now consider a simple system which merely reads all the data in a file to find the items it wants. No data base technology is used. If, on average, ten percent of the data was retrieved each time, then this simple system has a retrieval efficiency equal to the powerful DBMS. As it does not have the concomitant disadvantages, the overall efficiency is greater and at substantially less cost!

## EXPLORATION DATA STRUCTURES

Exploration data sets exhibit a wide variety of different structures for which no single one of the standard DBMS models is particularly appropriate. Figure 67.8 shows the structures of four typical exploration data sets, which are:

- 1) Aerogeophysical data in an archival form: positional data for track points along a flight line, followed by the geophysical measurements between the track points. Lines are grouped by map.
- 2) Aeromagnetic leveling data set: all traverse numbers, followed by all control line numbers, followed by data from all traverse/control intersections.
- 3) Geochemical analysis data in tabular form: records of sample number followed by the elemental concentrations.
- 4) Geochemical analysis data by batch: all sample numbers, followed by all concentrations of element 1, then all concentrations of element 2, etc.

Data set 1 is hierarchical. Data set 2 is a network. Data set 3 is a Relation. Data set 4 does not fit easily into any of the three standard models.

## DATA BASE TECHNOLOGY AND EXPLORATION DATA

Geochemical data, has a relatively low volume, predominantly tabular structure and a frequent requirement for row-oriented retrieval. This makes it an ideal candidate for a Relational DBMS.

Geophysical data has high volume, does not fit any one standard DBMS data model, and has a predominant requirement for large volume, mostly unselective, column-oriented retrieval. This makes it singularly unsuited for any type of general purpose





Figure 67.6. Four typical geoscience data sets.

DBMS. Indeed, as shown above, simple file access programs can be more efficient and less costly than access via a sophisticated DBMS. Relational technology would be the least appropriate. Forcing standard geophysical data into Relational structures would double or quadruple the size of the already large data sets and degrade retrieval efficiency in proportion.

This does not mean that data base technology per se is irrelevant to geophysical exploration data, only that standard DBMS are largely so. DBMS technology can be applied to the benefit of exploration data in two ways:

- 1) Adapting useful techniques and applying them outside the context of the DBMS - i.e. data independence for simpler file structures.
- 2) Development of a DBMS which is appropriate to exploration data - i.e. one founded on a model suited to the particular structures of exploration data.

#### DATA INDEPENDENCE AND EXPLORATION DATA

Jeffery and Giff (1976), with regard to scientific data in general, state that:

"Independence of data from the processing software is essential for any synthesis of scientific data because it is impossible to define all possible combinations of data format and structure at the time of writing the software."

Increasing use is being made of integrated geological, geochemical, and geophysical interpretations such as described by Eliason *et al.* (1986). In this context, Holroyd (1988) notes that exchange and integration of data is continually hampered by structural differences between data from different sources. To overcome this, it is necessary that data structures be independent of the software that accesses them. Too often, however, when one group receives a magnetic tape of exploration data from another group, they receive documentation describing the contents and must then write or modify a program to read the data - the data and applications program are clearly not independent. The techniques of data independence are not restricted to the DBMS and structured data base environment, however. Bradley (1982) demonstrates the problem of data independence and provides solutions with reference only to simple files and programs.

Data dependence on software is characterized by the "accompanying documentation" mentioned above. To achieve data independence requires that this documentation disappear from paper and reappear on the data tape as "metadata" - data which describes data (see Leong-Hong and Flaggman 1982). A standardized software interface can now read the "documentation" itself, and then perform the mapping between the application's request for data and the logical and physical content of the data set.

In other words, what is now a tedious and error prone task carried out by people, can become a standardized automated procedure - the fundamental *raison d'être* of the digital computer. This may seem somewhat ambitious and futuristic. To the data base technologist, however, it is a fully established, decades old, standard practice.

Given the (continually increasing) power of microprocessors, it is now eminently feasible to introduce full data independence right at the source of geophysical exploration data - the digital data acquisition system in the aircraft - and to carry the independence through the compilation processes up to interpretation and exchange of data sets for integrated studies. The cost of implementing such a standard would be more than covered by the time saved in future operations.

Figure 67.9 shows the basic architecture required. This is equivalent to, but much simpler than, the four levels in the DBMS architecture in Figure 67.6. Systems A and B, are any existing applications programs (= level 1 "users" in Figure 67.6). The utility routines (= level 2 "external views") translate the specific needs of each application into standard logical instructions to the data management system. The generalized logical modules (= level 3, "conceptual view") translate the logical instructions into actions to access the data (= level 4).

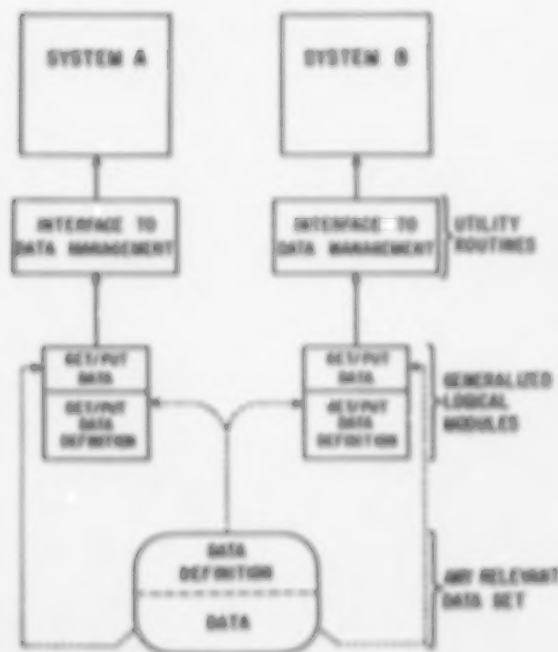


Figure 67.9. Data independence: the principal role of data management in an integrated processing system.

## DATA MODELS AND EXPLORATION DATA

A basic fact, as illustrated above, is that although most exploration data sets will fit into one or the other of the standard models, the complete range of data structures refuses to fit neatly into any one of the three models. Attempts to force the "ill suits" of structures into one model have been made (more than once) and produced results varying from unacceptable to disastrous. This means that a single data base management system cannot be used effectively for a data base containing more than one type of geoscience survey data. Different types of DBMS generally employ distinctly different languages to effect data storage and retrieval and very different internal storage structures. Hence the different data bases are totally incompatible. Users requiring access to more than one type of data must learn more than one data manipulation language, and integrated interpretations are severely hampered.

If one of the three standard models must be used, then the most applicable on the average is the oldest and simplest model, hierarchical. Many geoscience data sets are intrinsically hierarchical (e.g. Survey - map - line - station), and the "top-down" retrieval paths afforded by this model suit most retrieval needs, e.g. aeromagnetic applications regularly require specific lines from specific maps but never ask the "bottom-up" question "which lines on which maps have total field values of a specific magnitude"?

In a comprehensive system, a complete fit between data model and all data structures is an absolute requirement. If the data will not fit the standard models, then a new model must be used which fits the data. A fourth model exists (Holroyd 1984) which was derived by analysis of a large number of data structures from five geoscience survey disciplines (aeromagnetism, airborne gamma ray spectrometry, gravimetry, geochemistry, and drift sedimentology).

When the data sets were analyzed to their simplest components as logical objects isolated from their parent disciplines, it became possible to synthesize a single data model which fully describes all of the features of all of the many different data types studied, and which is applicable to geoscience data in general, not merely specific to the particular data sets studied.

The model is known as the "Algebraic model" as it defines data structures by vector algebraic expressions, and data manipulation processes by algebraic manipulation. Data structures conforming to any of the three standard models can be redefined as algebraic structures, as can data sets which do not fit easily into any one of these. To demonstrate (for proof see Holroyd 1988), the four data sets described in Figure 67.8, one conforming to each of the three standard models and one nonconforming, all fit easily into the algebraic model. Their struc-

tures, as described in algebraic data model notation, are as follows:

Archival aerogeophysical data (hierarchical) =

(Map (Line (Track) (Geodata) ) )

Aeromagnetic leveling data (Network) =

(Traverse) * (Control) - (Intersection)

GEOCHEMICAL ANALYSIS tabular data (Relational) =

(Sample, Cu, Pb, Zn)

GEOCHEMICAL batch analysis data (Non-conforming) =

(Sample) - (Cu) - (Pb) - (Zn)

The hierarchical, network, and relational geochemical data structures shown respectively in Figures 67.1 to 67.3 are definable as follows:

Hierarchical = (Area (Rock (Element (Sample, result))))

Network = (Area) * (Rock) * (Element) * (Sample, result)

Relational = (Sample, Rock, Area) (Sample, Element, Result)

Therefore, at least one model exists which, unlike any of the three standard models, can be used for a wide variety of different geoscience data tapes without having to force the majority into unnatural and inefficient structures. This means that a DBMS could be created which would effectively and efficiently serve the needs of integrated geoscience data processing.

## CONCLUSIONS

Data base technology has significant relevance to exploration data.

For geochemistry, the most relevant and beneficial development over the past decade has been the Relational DBMS.

Geophysics, on the other hand, has not benefited as much as it could from data base technology. A good reason for this is that neither geophysical data structures nor retrieval requirements are well suited to the standard DBMS.

The techniques of data independence, however, are highly relevant to geophysical data systems outside of the DBMS environment, and substantial effort should be made to fully adopt and apply these techniques.

Geophysics could benefit within the DBMS environment as well as by development of systems based on a model that does fit the particular structures and retrieval requirements of geophysical data and applications processes.

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## 68. Image Processing of Geophysical and Geochemical Exploration Data Sets

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### ABSTRACT

Image processing is a generalized term which covers a range of techniques used to correct, enhance, and classify continuous images. Digital image processing was brought to the exploration industry through remote sensing during the 1970s. Analysis of the large data sets involved led to the deployment of new graphics technology in both software and hardware.

Geophysical data of all forms are collected on grids or along profiles. These data are normally contoured to an image of the geophysical field, represented in vector graphics form as a contour map. With modern digitally recorded data, computer processing techniques involve contouring programs. The principal step in most of these routines is the creation of an interpolated rectangular or square

grid of values from the profile data prior to line contouring. The realization that this grid represents an interpolated continuous image of the measured geophysical field opens the techniques of image processing to the geophysicist.

Image processing readily allows enhancement of gridded geophysical data sets and provides a powerful tool for retrieving spatial information. Interactive routines provide the geophysicist with the data compression to enable the full range of data to be accessed in one image, filtering techniques for wave length discrimination, and edge enhancement routines for lineament identification. They also allow the simultaneous registration of different gridded data sets and provide statistical techniques to help in the identification of relationships between them.

## 69. Computer Techniques for Exploration Using Vulcan Mapping/Graphics

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### ABSTRACT

BHP-Utah is an Australian-owned international mining company involved primarily in coal and base and precious metal activities. After using an assortment of programs developed in-house, our exploration group in San Francisco purchased a package from Applied Mapping Systems to replace the old mapping programs and to provide capabilities for viewing and interpreting information on a graphics screen interactively. Since the implementation of this system over two years ago, we have gained some valuable insights into techniques and advantages of this approach.

Three main aspects of our experience are discussed:

1. Preparation of surface and drill hole data, including some critical decisions that must be

made when data is intended for computerization.

2. Hardcopy map products, providing some examples of geological, geochemical and cultural information being integrated into a single map.
3. Interpretation and manipulation of various types of information using an intelligent, graphics workstation. This last feature will form the basis for most of this presentation, with examples of display techniques the geologists have found most useful, various ways of looking at information, and the implications of chosen data base structures.

Some limited discussion of the ore reserves/mine planning aspects of the package are included, as well as a few brief comments on hardware selection.

## 70. Considerations in the Selection of Microcomputer Equipment and Software for Geophysical Data Processing

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### ABSTRACT

Microcomputers have changed the way geophysicists do their jobs and, to some extent, what the geophysicist's job entails in an exploration environment. The full implications of this change are not yet fully understood as the micro revolution is still in progress. However, we do recognize a number of negative side effects which can be avoided or minimized by the careful consideration of the needs of the user organization.

Prior to making major selections of equipment or software, the potential user should first examine his computer needs in general terms within his work environment. Questions to be answered include: how is data currently being treated; how many people will need to use these facilities; what is their level of computer sophistication; how are they distributed geographically; and what growth path is anticipated in terms of types of problems being worked on and numbers of people involved?

Once it is decided that a microcomputer is the correct solution, a number of questions need to be

examined regarding the hardware/software side of the issue. While micros have been around long enough that a de facto operating system standard exists in the form of MS-DOS, there are still many pitfalls awaiting the potential user. Some of the major points to be considered at this stage are: 1) The requirement and cost of converting existing methods and software to a new computer system. 2) Serviceability of hardware and support for software. 3) Costs of hardware/software including all required peripherals. 4) Selection of software, either from commercial vendors or through in-house development. While in-house products can be very effective, the development costs are substantial (~3.10 times comparable off the shelf commercial products) and may be difficult to support in the long term.

Whereas general business-type software has flourished with the micro, the geophysical market is still relatively small. Complete packages which go from data dumping, editing, plotting and interpretation are only now starting to appear.

## 71. Putting Expert System Technology to Work

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Expert System Programming Methods help create programs that model the inferential reasoning, and practiced decision making of human experts. This paper looks at three broad classes of expert system programs: Computer Based Consultations, which are a new form of literature. Expert Data Base Reporting

Systems, and Intelligent Sensor Advisors which make large and complex equipment responsive to operators. Examples of each type of program will be demonstrated, and some practical approaches for implementing the technology will be described.



## 72. Expert Systems and Their Use as Exploration Assistants

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### ABSTRACT

An expert system is a computer software system which uses Artificial Intelligence methods to solve problems and give advice simulating a human expert. Unlike conventional programs it can manipulate knowledge and "fuzzy" information as well as numeric data, and explain to the user why certain information is required and how a decision is reached.

The three principal components of an ES are:

1. the knowledge base or stored expertise supplied by specialists in the specific problem domain
2. the inference engine incorporating the problem-solving mechanism
3. the user interface which provides the working environment

Expert systems as exploration assistants can be divided into two groups, integrated and domain specific, depending on the scope of the knowledge base.

An integrated ES, such as PROSPECTOR, is based on models of deposits combining a wide range of geological, geophysical, geochemical, and geographical information. PROSPECTOR-II is being used at the U.S. Geological Survey to evaluate the mineral potential of selected regions. In a consultation the ES requests information on rock types, ages, mineralogy, geochemistry, and geophysics which it then matches with models of mineral deposits described in its knowledge base. It produces a ranked list of the likelihood of these deposits occurring in the given environment. A domain specific ES is restricted to a narrow scope within one discipline, such as rock geochemistry, EM geophysics, or a drilling operation.

Expert systems have proven most effective when applied to specific, relatively well-defined problems, as demonstrated by their use in oil exploration. In the mineral industry expert systems are used primarily at the extraction and processing phases; a few are under development for exploration, where their potential as advisors with total recall is likely to be realized in the near future.

### INTRODUCTION

An expert system (ES) uses stored knowledge provided by experts to reach decisions and give advice

in a manner which would be considered intelligent if done by a human. It is a practical application of Artificial Intelligence (AI).

While AI has been evolving as a branch of computer science since the 1950s, expert systems became a reality in the late 1970s when AI workers recognized that a program, in order to solve problems, must possess knowledge in addition to formalisms and inference procedures; the "intelligence" of the system depends on its knowledge of the specific problem area. Reflecting this essential characteristic, expert systems are also known as knowledge-based systems.

The ability to store human experience and provide advice based on total recall of that knowledge is a prime qualification for an exploration assistant. To be a useful advisor, however, the expert system must also be capable of handling the types of information on which decisions are based and suitably processing it.

Exploration decisions generally relate to WHERE to survey (area selection), HOW (methods, intensity), and WHAT does it mean (interpretation). The types of information include both quantitative, such as geophysical and geochemical results, and qualitative, such as geological reports and maps, economic factors, and accessibility. The information is often incomplete and its quality varies from precise to a "rough guesstimate"; frequent use of qualifiers such as mostly, several, few, and likely indicates that "fuzzy" data is common. The decision process must include both the treatment of numeric data by statistical or other methods and the use of heuristics, intuition, and rules of thumb based on practical experience.

An expert system can deal with these factors and has the potential of being a very competent and helpful exploration assistant.

### BACKGROUND

For a more detailed outline of expert systems than is possible here, attention is drawn to four among the many introductory and review books: Harmon and King (1981); Harmon et al. (1988); Rauch-Hindin (1986); and Waterman (1984). Useful articles on the subject appear in periodicals such as PC Magazine, BYTE, AI-Expert, AI PC, and The AI Magazine. More specialized papers are published in Expert Systems: The International Journal of Know-

edge Engineering, and in journals and proceedings of professional associations such as The Institute of Electrical and Electronics Engineers (IEEE), The Association for Computing Machinery (ACM), and various AI organizations. In this rapidly evolving field, new publications, and new software and hardware products are appearing at a fast rate. Some of the references in this paper will become outdated early in the useful life of this volume. The Turing Institute Abstracts provide regular updates of AI publications.

## COMPONENTS

The three principal components of an expert system are the knowledge base, the inference engine, and the user interface. In a consultation with an expert system the user poses a problem through the interface to the inference engine which scans the knowledge base for relevant information, processes it, and provides responses. The components and their interaction are shown in Figure 72.1.

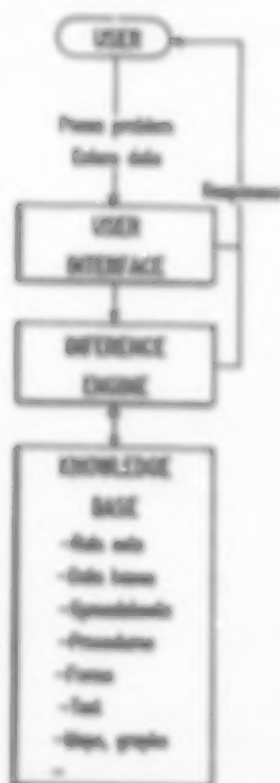


Figure 72.1. COMPONENTS OF AN EXPERT SYSTEM AND THEIR INTERACTION. The user poses the problem, enters data, and receives responses through the user interface. The interface communicates with the inference engine which in turn interacts with the knowledge base, processes the information in it, and returns the results to the user.

## KNOWLEDGE BASE

The knowledge base comprises the expertise contributed by specialists in the problem domain and is the most significant contributor to the usefulness of an expert system; the advice and conclusions reached by the ES can be only as good as the knowledge and information on which they are based. The knowledge base consists of facts and data in various forms, and rules and relations governing them.

## KNOWLEDGE REPRESENTATION

Several ways have been devised to represent reasoning expertise including pieces of text, program logic, collections of predication; the three most common methods are rule sets, frame-oriented structures, and semantic nets.

A rock classification example can be used to illustrate these knowledge representation methods: given that the Mode of occurrence is volcanic, the Color is nearly black, and the Texture is felsitic, then the rock is very likely basalt.

A rule specifies a recommendation or strategy in the form:

IF premise THEN conclusion or  
IF condition THEN action

Figure 72.2 shows the rule representation of the rock example. Note that the qualifiers "nearly" (for black) and "very likely" (for basalt) are not accounted for at this time, but will be later when discussing confidence factors.

Both frame and semantic net representations use a network of nodes connected by relations and organized into a hierarchy. Each node represents a concept that may be described by attributes and values associated with the node. Nodes lower in the hierarchy automatically inherit the properties of higher level nodes. These methods are particularly suitable for representing taxonomic information, such as ore deposit descriptions.

```

IF premise THEN conclusion
or
IF condition THEN action

IF Mode = volcanic          and
   Color = black (F 80)      and
   Texture = felsitic
THEN Conclusion = basalt (F 80)
  
```

Figure 72.2. PRODUCTION RULE METHOD OF KNOWLEDGE REPRESENTATION. If the facts in the premise portion of the rule are true, then the conclusion is valid and the rule is said to have "fired".



Figure T2.3. FRAME METHOD OF KNOWLEDGE REPRESENTATION For description see text.



Figure T2.4. SEMANTIC NET METHOD OF KNOWLEDGE REPRESENTATION For explanation see text.

The frame representation of the rock example is given in Figure T2.3. The hierarchical network of nodes shows the relationship of subclasses of the concept rock; our example falls in the igneous-basalt branch. An individual node consists of "slots" or attributes which can be filled by values or by procedures, i.e. instructions on how values can be found. The slots for the node basalt are the attributes Name, Mode (volcanic), Colour (black), and Texture (felsitic).

The semantic net form is seen in Figure T2.4; the nodes are connected by arcs or links which de-

fine the relationship between them, such as "is-a", "has-property".

The inheritance principle is demonstrated by the fact that the node "basalt" will possess all the characteristics of "igneous" and "rock", the nodes above it in the hierarchy.

## DATA FORMS AND TYPES

The data portion of the knowledge base can be entered interactively as requested during a consultation, can be generated by a program procedure as needed, or can be extracted from stored data bases, spreadsheets, or other files.

For example, in a geochemical expert system, field and laboratory data might be stored in a relational data base, and map information in a graphics file. Programs to carry out special statistical treatment or produce maps and other graphics could be developed and compiled separately. The expert system will access all these facilities and respond to additional information entered by keyboard or mouse at consultation time.

The types of data include numeric (Zn=150), logical (true/false), and text (colour=green). Variables can be specific or fuzzy (assume more than one value at the same time). Values can be precise, uncertain, or unknown, as specified by a Certainty Factor CF.

## INFERENCE ENGINE

The inference engine processes the information in the knowledge base to reach conclusions. It incorporates the methodologies for the reasoning or decision process to be followed in a consultation.

Rules are processed by sequential match-one-one steps. The premise (IF portion) is checked against the currently known data; if the conditions are satisfied, the actions specified by the THEN portion are executed and the rule is said to be "fired". The firing may create new facts to be added to the old and used by other rules.

The control mechanism for rule-based systems comprises two basic strategies, backward and forward chaining.

In backward chaining, or goal-oriented control, the inference engine attempts to find a value for an overall goal by recursively finding values for subgoals. Only those rules whose conclusion could produce a value for the immediate goal are considered. An unknown premise in a candidate rule becomes a new subgoal in the recursion. In an exploration example, backward chaining would be used when the problem is posed as "what is the likelihood of a certain type of deposit for a given set of observations?"; the goal is pre-defined by the specified type. In forward chaining, or data driven control, the inference engine determines the effect of all known facts on the unknown variables or facts by firing all rules

often premise is established as true. In the exploration example this procedure would be followed if the problem requested "what are the more likely types of deposits compatible with a given set of observations?"; a number of possible goals would be sought and ranked.

A flexible inference engine will perform both forward and backward chaining at the user's request.

In frame-based systems, where knowledge is organized in related nodes or subgoals, the reasoning process is controlled by procedures associated with the attributes (slots) for the nodes. Various types of actions or procedures can be executed depending on the value of the attributes: *d-added*, *d-removed*, *d-needed* procedures would be activated when new information is added, an existing value is required, or an empty slot needs information respectively. The procedure may modify values in other slots in a process which continues until the goal is achieved or all possibilities are exhausted.

The hierarchical structure of the frame system implies inheritance of features from one level by all related lower levels.

Semantic nets also have the hierarchical inheritance property. The arcs connecting the nodes in the network direct the search according with the relation they define.

## REASONS AND EXPLANATIONS

In addition to requesting information when needed and providing conclusions, the inference engine will give reasons why it needs the information and explain how it reaches a decision.

These attributes allow the user to monitor the path of the conclusion and to modify the appropriate parameters if a change in the process is desired. This accountability is built into the knowledge base as the system is developed and is necessary to give the user confidence in the answers.

A rock geochemistry expert system might include:

[DS group] - Rule (NAME) of D.R.E. when sample required.

[User exp] - Why

[ES response] - The immediate goal is to establish whether element values are consistent. The next step is needed to place the sample in the appropriate group for comparison.

## CERTAINTY FACTORS AND FUZZY VARIABLES

Some decisions, especially in exploration, have to be made with information which is of doubtful accuracy, incomplete, or missing. These real life situations must be taken into account if an expert system is to be realistic and useful. The inference engine can use a calculus of uncertainty to reach conclusions with information ranging from unknown,

through a gradation of certainty, and up to definite. It can also process fuzzy sets, or variables which can have two or more values simultaneously.

Certainty factors (CF) expressing the confidence, correctness, or likelihood can refer to a variable value, a premise, a conclusion, or an entire rule.

Certainty factors could be used to refine the rule illustrated earlier:

```
IF Mode = volcanic and
Color = black CF 80 and
Texture = basaltic
THEN Rock = basalt CF 80
```

The variable Colour=black and the conclusion Rock=basalt are given a certainty factor of 80 and 80 for the qualifiers "mostly" and "very likely" respectively, in a scale of 0 to 100.

Fuzzy variables can be illustrated by the following rule:

### RULE 1

```
IF alteration = "high"
THEN Environment = "good" CF 70
```

### RULE 2

```
IF Pathfinder = "normal"
THEN Environment = "fair" CF 80
```

The conclusion would use both values of Environment in seeking the goal, with "fair" having the greater weight.

## BUILDING AN EXPERT SYSTEM

Once a suitable problem has been selected, the expert system is built by transferring the specialized knowledge from human experts to the computer, a process called Knowledge Engineering. The essential members of a development team are the domain expert and the knowledge engineer or AI specialist; the former contributes the problem expertise, and the latter systematically organizes it into a model using suitable software and hardware tools.

Occasionally both functions can be performed by the domain expert, such as a geologist, who has sufficient familiarity with the system building procedure and tools.

## LANGUAGES AND SHELLS

The software tools of expert systems include languages and shells. Although systems can be implemented using common procedural languages such as FORTRAN, PASCAL, BASIC, or C, the concepts of AI are more conveniently and efficiently processed by symbol-manipulating languages like LISP, PROLOG, SMALLTALK, or OPS5. Several versions and dialects of these languages have been developed for various computers.

LISP (from List Processor) originated at MIT under John McCarthy in 1957 (McCarthy 1978)



and is now widely used, particularly in the United States. It manipulates symbolic data represented as linked list structures. A list is a collection of items enclosed in parentheses, each item being either a symbol or another list. LISP, being a relatively low-level language, provides great flexibility in AI programming. It is, on the other hand, notorious for requiring a lot of memory and computing power, thus making implementations on personal computers difficult and often inefficient. Two recent hardware developments will alleviate some of these problems, 32-bit microprocessors and Lisp machines on a chip.

PROLOG (from Programming Logic) was officially formulated at the University of Marseille under Alain Colmerauer about 1970 (Colmerauer 1982), and was expanded at the University of Edinburgh (Clarkson and Mellish 1984). It is rapidly spreading from its European base and has been designated the language of Fifth Generation computers in Japan (Feigenbaum and McCorduck 1982). PROLOG embodies the concept of declarative or descriptive programming; the user describes the problem in a logically coherent and correct manner and leaves to the computer the task of working out and executing the steps necessary to solve the problem. This approach is markedly different from the procedural method used in conventional programming, whereby specific commands to perform each step in the solution must be given to the computer. A PROLOG program consists of relationships of objects, with facts and rules about them. It is like a database of facts about which one can make inferences and ask questions. Backtracking is the technique used to seek matching answers; this is a method of trying a path to the solution and, if that fails, backing up to a previous branching point to follow an alternative route. PROLOG is particularly suitable for pattern matching, natural language, and expert system applications where numeric calculations are not a major requirement, although a new version of the language with good numeric capabilities is expected soon. A Prolog representation of the fact that a mineral contains a principal element could be:

`contains (mineral, element)`

where `contains` is the predicate, and the objects `mineral` and `element` are the arguments.

The facts in the data base could include:

`contains (chalcopyrite, cu)`  
`contains (pyrite, fe)`  
`contains (sphalerite, zn)`  
`contains (hematite, fe)`  
`contains (muscovite, si)`

Questions can now be asked:

**Find a mineral containing Cu**

**Q:** `?-contains(M,cu)`

**A:** `M=chalcopyrite`

**List Zn minerals**

**Q:** `?-contains(M,zn)`

**A:** `M=sphalerite; (first answer, look for more)`

`M=muscovite; (second answer, look for more)`

`no (no more)`

**Show principal element in hematite**

**Q:** `?-contains(hematite,E)`

**A:** `E=fe`

**Find a Pb mineral**

**Q:** `?-contains(M,pb)`

**A:** `no (none found)`

SMALLTALK, originally developed in the 1970s at Xerox Palo Alto Research Center (PARC), implements the concept of object-oriented programming. A fact or an item of data is defined as an object which receives messages or instructions to perform certain procedures on itself. This approach contrasts with that of most languages, where active procedures act on passive data that is passed to them. For example, in the Fortran expression `SQRT(X)` a value of `X` would be passed to the function `SQRT` which would compute the square root. In SMALLTALK this might appear as `X.sqr`, where the object `X` receives the message `sqr` to perform the square root operation on itself. Objects are structured in classes and subclasses with inheritance properties. SMALLTALK is very useful for simulation and modelling applications.

Several special knowledge engineering languages have been developed including LEXPS (from Xerox), OPS1, and OPS2 (from Carnegie-Mellon), KEE (Knowledge Engineering Environment, from Inference), and ART (Advanced Reasoning Tool, from Inference Corporation).

The basic languages of AI, LISP, and PROLOG, are best suited for building expert systems "from the ground up", with an integrated inference engine and for fast execution. Their use requires a considerable programming effort.

## SHELLS

A shell can be defined as a pre-developed core around which an expert system can be built by adding domain-specific knowledge. While their capabilities vary over a wide range, all shells include some knowledge representation schemes, an inference engine, some means of describing a problem, and a

ory of monitoring the solution process. Good shells usually allow interaction with external programs and data, such as database managers, graphical and mathematical procedures, and spreadsheets.

Although an expert system built around a shell may be less run-time efficient than one especially designed using a basic language like LISP or PASCAL, a notably chosen shell speeds up development time and allows rapid prototyping. It may also allow the domain expert to do much of the knowledge engineering on his own, rather than rely entirely on an AI specialist. Some shells incorporate an inductive process whereby the domain expert enters representative facts and data on the problem and the shell then builds the relations and rules; the system acquires its knowledge from representative examples. This method can be very useful in situations where the human expert can clearly communicate WHAT he does, but has difficulty explaining WHY.

Shell development is perhaps the most dynamic area of AI; new products with more and better features are appearing at a fast rate, with prices ranging from under \$100 to over \$10,000. Those running on PCs are making expert systems affordable and more accessible, thus greatly helping in spreading their popularity. Some shells available in 1987 include ADS, CLASSIC, EXSYS, Gera, RED, Personal Consultant, and VP-Expert.

## HARDWARE

AI work traditionally has been carried out at universities and research establishments on dedicated AI workstations incorporating symbolic processors. Apollo, Sun, Symbolics, Texas Instruments, and Xerox are among the better known. Prices range generally between \$20,000 and \$100,000.

Three significant developments are now helping to bring AI/ES out of the laboratory and into the workplace: powerful 32-bit personal computers, good language and shell implementations on PCs, and symbolic processors on a chip which can be used as co-processors in a PC. It is now reasonable to expect the imminent implementation of powerful expert systems on hardware priced in the \$1000 to \$10,000 range.

## USER INTERFACE

The interface provides the practical interaction between user and system. It includes the hardware I/O devices such as keyboard, mouse or tablet, voice-activated components, display monitor, printer, or plotter. It also requires software to guide the user in entering information, to monitor the progress, and to provide answers and reasons.

A combination keyboard and mouse is the most common input configuration. A low flicker display

with a resolution of 640 by 350 pixels or better is recommended.

Interaction varies from simple menu selection to elaborate graphics-driven screen pointing.

## APPLICATIONS

Expert systems have been used to advise, analyze, categorize, communicate, consult, design, diagnose, explain, explore, forecast, form concepts, identify, learn, manage, monitor, plan, present, retrieve, schedule, train, and tutor (Michaelsen *et al.* 1987). Some areas of application include medical diagnosis, real-time industrial process control, mineral and oil exploration, banking, stock market, and other financial activities.

The oil industry was quick to recognize the potential of expert systems; many systems are in use there. A survey of mining geological establishments indicates some interest but little actual work in this field. In the mining industry expert systems are being used in the exploration and processing phases (Pytel *et al.* 1987; Perkins and Price 1983). A few exploration expert systems are under development and have reached the experimental and prototype stage.

## EXPLORATION EXPERT SYSTEMS

Expert system applications in mineral exploration can be classified into two broad groups, integrated and domain specific. An integrated model ES would have a wide-ranging knowledge base comprising the fields of geology, geochemistry, geophysics, geography, and economics.

A specific model would be restricted to a problem within one of the above fields.

## INTEGRATED MODELS

### PROSPECTOR

PROSPECTOR is an expert system which addresses the most general exploration concepts: given a set of observations in a specified region, determine the mineral potential of that area. In a consultation with PROSPECTOR the geologist is asked questions on geological, geophysical, and geochemical observations. The ES matches this information with a series of mineral deposit models in its knowledge base and provides a list of deposit types ranked by their likelihood of occurrence.

The original PROSPECTOR was developed at SME International in co-operation with the United States Geological Survey between 1974 and 1983 (Duffy 1983). It was credited with locating an occurrence of a molybdenum deposit at Mount Tabor, in Washington State, which had eluded experienced geologists (Campbell *et al.* 1982). Work on it has continued at the U.S. Geological Survey, which in 1984 published details of *rePROSPECTOR* for the IBM PC type of computers (McCannan 1984).

The most recent version, PROSPECTOR-II, departs substantially from its predecessors and is patterned after INTERNIST-I, an ES used for medical diagnosis.

The following description is by Richard McCammon of the U.S. Geological Survey:

"PROSPECTOR-II is designed to aid geologists in evaluating the potential mineral resources within a given geographic area. It operates by allowing the geologist to volunteer information about an area and matching this information with deposit models stored in a knowledge base. The result is to produce a ranked listing of the types of deposits most likely to occur within the area...

In its present stage of development (1987), PROSPECTOR-II accepts information about the age of the rocks, the rock types, minerals, geochemical elements, geophysics, and associated known deposits." (McCammon, U.S.G.A., Reston, Virginia, USA, personal communication, 1987).

The U.S. Geological Survey has expanded the knowledge base from the 33 models in the final SRI version to 88 (summer 1987). Knowledge representation in PROSPECTOR-II is object or frame oriented, whereas the earlier versions used inference networks and were essentially rule-based. It is implemented on a Xerox 1108 AI workstation and runs interactively; most input is done by selecting by mouse the appropriate choice from the menu presented by the user interface. A consultation takes 15 to 20 minutes. The U.S. Geological Survey uses PROSPECTOR-II for regional mineral resource assessment and intends it to perform at or near the level of an experienced economic geologist.

## GEOVALUATOR

This system is being developed at the University of Georgia under the direction of G.S. Koch. It is intended for the evaluation of mineral resources in the United States and involves a two-stage application of PROSPECTOR. Dr. Koch is also participating in the development of a system based on the combination of knowledge semantics and data semantics, rules, and nets (Koch and Papacharalampos, in press).

## PIERO

This experimental system is the product of a thesis project by J.L. Cottalorda at the Ecole Nationale Supérieure des Mines de Paris and at the Université de Nice. Although it shares some of the inference net concepts and forward chaining approach of the SRI PROSPECTOR, PIERO uses a substantially different inference engine and a revised form of data representation. It was written in FORTRAN (Cottalorda 1986).

## SPECIFIC SYSTEMS

The following systems deal with particular aspects of exploration. Although most were developed for oil exploration, (FINDER, GES, and SERGE are nota-

ble exceptions) they are briefly described here since many of their concepts are also applicable in the search for mineral resources. More detailed descriptions of some of these systems can be found in Waterman's book (Waterman 1986).

## DIPMETER ADVISOR

This ES was developed by Schlumberger-Doll Research for geological interpretation of rock conductivities measured by borehole dipmeter soundings. Knowledge is rule-based and the inference engine uses forward chaining. It runs on Xerox workstations (Smith and Baker 1983).

## DRILLING ADVISOR

This system, jointly developed by Teknowledge and Societe Nationale Elf Aquitaine, diagnoses the factors causing sticking of the drilling mechanism in the borehole and recommends suitable measures to prevent or alleviate the problem. The knowledge base is in the form of rules relating symptoms and likely causes within particular geological formations. The inference engine controls the rules by backward chaining (Hollander and Iwasaki 1983).

## ELAS

Expert Log Analysis System is a development of Rutgers University and Amoco Production Research. It assists in the control and interpretation of Amoco's INLAN system for well-log surveys by recommending the method of analysis, warning of inconsistencies, and summarizing the INLAN results. It is essentially a rule-based system with an elaborate graphical user interface (Apte 1982).

## FINDER

While FINDER is more an algorithmic Pascal program than an expert system, it uses some principles of AI to aid in locating mineral target areas by combining Bayesian statistics and area of influence techniques. The basic objective is to differentiate between samples from mineralized and those from barren areas. Up to four variables, geological, geochemical, or geographical, can be specified. Control models for the barren area and mineralized target are required for comparison. FINDER was developed by Donald Singer at the U.S. Geological Survey (Singer 1985).

## GES

The Geo Expert System is being developed by Luciano Martin of CASE, Toronto as a series of specific narrow-domain expert systems which can be interlinked into a general integrated ES. Each subsystem provides conclusions on its specific field such as rock geochemistry, EM response, or mineralogy. These results can then be used as input to a more

general model. GES uses Guru as the main tool and relies on extensive interaction with external data bases and supplementary programs for statistical and graphical manipulation. The knowledge base is mostly in the form of production rules which can be controlled by either forward or backward chaining. It is being implemented on PC/XT/AT/PS2 and compatible personal computers.

## HYDRO

This is an SRI development intended as an interface to the hydrological simulation program HSPF. HYDRO uses knowledge about soil type, land use, vegetation, and geology to estimate suitable parameters to be used in the simulation model to assess how precipitation is distributed in the watershed. It is patterned after the original PROSPECTOR, with which it shares the combination of rule and semantic net method of knowledge representation (Gaschnig *et al.* 1981).

## LITHO

LITHO is an interpretation assistant for oil-well log data developed by Schlumberger. It combines the density, resistivity, radioactivity, and other parameters from the log with knowledge about the geological environment to define rock characteristics such as porosity, permeability, texture, and composition. A pattern recognition program is used to obtain features from the logs. Knowledge is represented by rules, and control is carried out by backward chaining (Bonnet and Dahan 1983).

## MUD

MUD is a drilling fluids consultant developed by Carnegie-Mellon University and N.L. Baroid. It identifies problem sources in fluids and recommends remedial action. It deals with contaminants, chemical imbalances, and high temperature and pressure to advise on optimal fluids. Knowledge is in rules controlled by forward chaining (Kahn and McDermott 1984).

## SERGE

Système Expert en Reconnaissance Géochimique is a development of BRGM and the Laboratoire de Recherche en Informatique de l'Université de Paris Sud. It is a rule-based system for the interpretation of geochemical anomalies using base-metal models in the Brittany region of France (Bonney *et al.* 1987).

## CONCLUSIONS AND PROJECTIONS

Expert systems, with their capability to process both stored information and knowledge, have proven

their usefulness and are becoming the most powerful and convincing vehicle for bringing Artificial Intelligence techniques out of the research and into the practical work environment. Like most new technologies, they have occasionally failed, usually when they were used in unsuitable situations and with unrealistic expectations. They have been most successful in specific, clearly defined problems of relatively narrow scope where human expertise can be well synthesized. An expert system should appropriately be considered an assistant, not a substitute, for a human worker. When properly applied, the ES can enhance the ability of the specialist to make sound decisions consistently and can raise the level of his work above his potential capability. Industry studies indicate that experts who would normally perform at a level of 75 percent of what is humanly possible can increase the level to 85 percent (Rauch-Hindin 1986).

The use of expert systems for exploration of natural resources has been restricted generally to the oil industry; mine explorationists have been very slow in accepting this recent computer technology. Yet, many aspects of mineral exploration are ideally suited to expert systems.

While integrated systems like PROSPECTOR point the way to the ultimate scope in exploration, their usefulness can be severely compromised by their generality and possible lack of reliability in some details. For example, an accurate reply to a question like "is Cu anomalous?" might require a specific expert system in its own right.

The first significant successes of expert systems in mineral exploration are likely to result from applications dealing with specific, narrow problems such as planning a geochemical or geophysical survey, defining a metallogenic area from soil and stream geochemistry, recognizing deposit signatures from rock geochemistry, monitoring and optimizing the operation of a geophysical instrument, interpreting a particular type of geophysical survey, and evaluating mineralogical observations. Expert systems will also gain popularity as "intelligent" geological reference data bases and for tutoring in exploration techniques, an aspect of particular interest to developing countries.

Very powerful and economical personal computers and the availability of affordable software tools are making the use of expert systems as assistants in mineral exploration increasingly attractive.

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# **Integrated Case Histories**



# 73. The Role of Geophysics and Geochemistry in Sulphide and Precious Metal Exploration in the Light of Some Recent Ore Discoveries in Finland

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## ABSTRACT

The Proterozoic portions of the Precambrian bedrock in Finland, which host most of the major outcropping sulphide orebodies detected so far, are characterized by schist belts. These hamper direct geophysical exploration because they contain pyrrhotite-bearing graphite schists which are sources of magnetic and electromagnetic anomalies, and impede direct location of ores. However, the geological models constructed from computational geophysical interpretation and lithogeochemistry have proved invaluable in the search for blind sulphide orebodies.

Some areas where low-grade sulphide ore deposits had previously been found have now turned out to be promising in terms of precious metal ores. Priority in exploration for precious metal ores is given to either overburden geochemistry or geophysics, depending on the ore type and the regional geology. The IP method has proved an effective tool for locating certain types of precious metal deposits.

## INTRODUCTION

The metamorphosed Precambrian bedrock of Finland consists of Proterozoic and Archean rocks, of which the latter occupy large areas in eastern and northern Finland. The Proterozoic portions, which host most of the major outcropping sulphide orebodies detected so far, are characterized by granitoids and schist belts. Abundant pyrrhotite-bearing graphite schists, or black schists, which cause both magnetic and electromagnetic geophysical anomalies and geochemical anomalies, occur in these belts. The Archean part is composed of extensive granite gneiss areas and greenstone belts. The bedrock is covered largely (approximately 96 percent) by Quaternary deposits composed of till, sand, and clay. A simplified geological map of Finland showing, among other things, the location of the sulphide and precious metal orebodies discussed in this paper, is given in Figure 73.1.

The most economically significant ore deposits of the main sulphide ore belt, which runs across the country from northwest to southeast, are located in an area between a negative gravimetric anomaly and the Archean basement complex. The main sulphide ore belt manifests itself as a distinct barium anomaly on the national geochemical maps compiled on the

basis of one composite sample/300 km² and published by the Geological Survey of Finland.

The graphite-bearing schists hamper the use of geophysical methods in direct exploration. Airborne geophysical surveys, which have been conducted since the early 1950s from various altitudes, have not yet succeeded in detecting a marked sulphide ore deposit in the Proterozoic schist areas. The outcropping ore deposits have been discovered with the aid of indications given by ore floats; detailed surface investigations with various exploration techniques, such as extensive geophysical ground measurements; and the geological information deduced from airborne geophysical surveys. Since the 1970s, exploration for sulphide ores has had less success. Deep exploration has replaced conventional exploration in the environment of some operating mines, but it is expensive and slow.

This paper deals also with the results of follow-up studies leading to new ore discoveries in some of the areas already described by the author (Ketola 1979) in his lecture at Exploration '77 dealing with indirect exploration of copper ores. These are the Vuonos Cu-Co orebody at Outokumpu, the Pahlavuoma Cu orebody at Kittilä, and the Enonkoski Ni-Cu orebody at Laukunkangas.

The author (Ketola 1979) has earlier discussed in detail the use of petrophysics in efforts to unravel the causes of geophysical anomalies, and as an aid to computational interpretation. Thus, the present paper gives fewer density ( $\delta$  in gm/cc) and susceptibility ( $k \times 10^{-5}$  SI) values despite the important role played by petrophysics in the studies. To save space and make the text more readable, the units are omitted.

## NEW TRENDS IN EXPLORATION

This section reviews the new geophysical and geochemical methods introduced within the last ten years and applied in investigations of the ore deposits that are the subject of this paper. The development of exploration geophysics and geochemistry in Finland has been treated by Ketola (1986) and Kauranne (1986).

## GEOPHYSICS

The main new applications of geophysics are computational interpretation, imagery of low-altitude air-



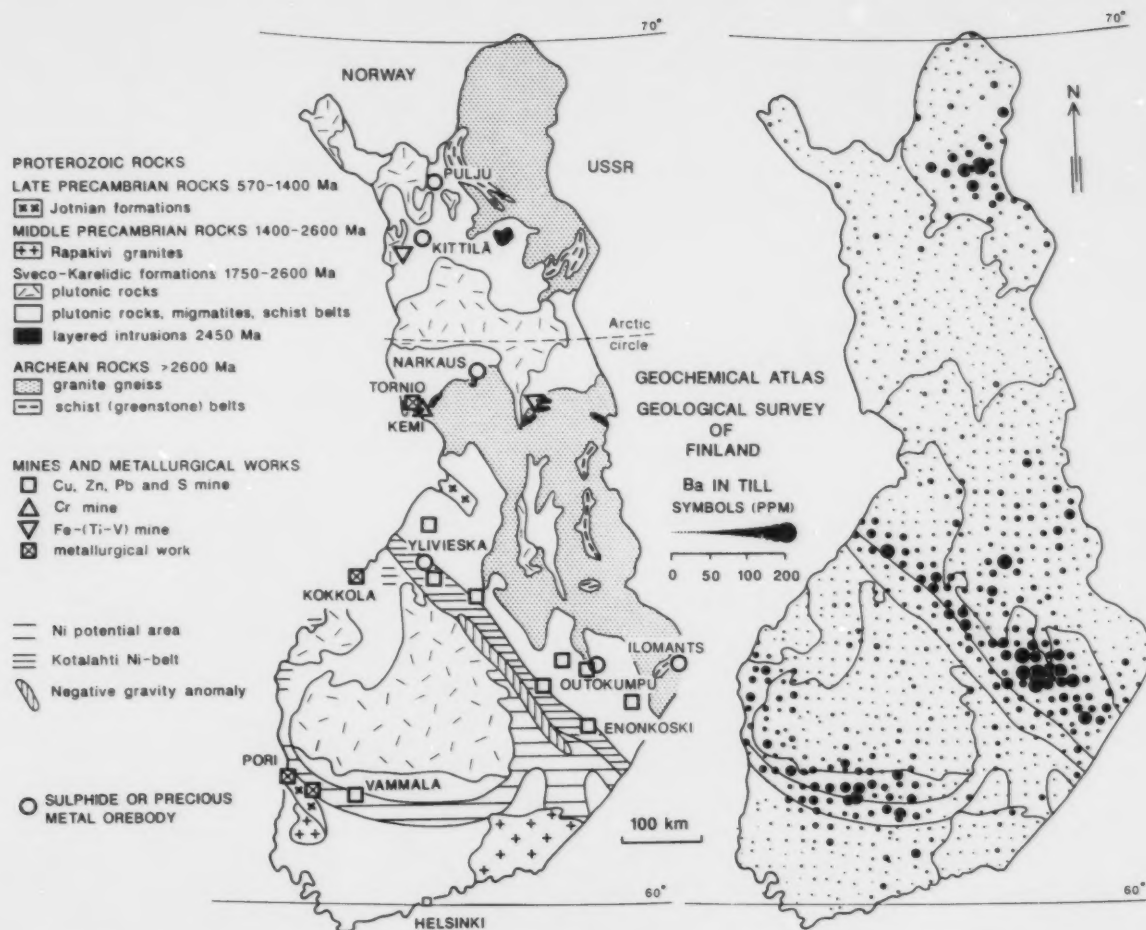


Figure 73.1. Location of sulphide and precious metal orebodies in Finland.

borne geophysical survey data, and the use of electromagnetic methods in deep exploration.

Computational geophysical interpretation is done via a video display terminal as continuous co-operation between geophysicist and geologist, the aim being to generate an increasingly accurate geological model with the aid of the geological and petrophysical data produced by drilling, as it proceeds. At the various stages of the interpretation, in which the average petrophysical data of the rocks are used quantitatively, the emphasis is on the ability of the geophysicist to elaborate on the geological model within the constraints of the interpretation models.

The magnetic and electromagnetic low-altitude data of the Geological Survey of Finland, measured with a line separation of 200 m from a flight altitude of 40 m, are excellent material for imagery. The electromagnetic data are measured with a wingtip system having a coil separation of 21 m and a frequency of 3200 Hz. Both gray-tone images and

principal component analysis with subsequent colour compositing of airborne data have proved useful; e.g. in delineating geological structures, in locating mafic bodies when prospecting for Ni-Cu ores, and in locating ore-potential lithologies that do not crop out.

In areas where the abundance of graphite schists is low, transient and multifrequency EM equipment with high depth penetration, such as Geonics EM-37, Maxi-Probe EM-16, or the new Gefinex-400 ( $f = 2 \text{ Hz}$  to  $20 \text{ kHz}$ ) manufactured by Outokumpu Electronics, has been used in deep exploration to trace the deep-seated continuations of orebodies and to establish geological structures.

A reference magnetometer, which allows the survey data to be corrected for the diurnal variation in the Earth's magnetic field, is currently used in magnetic ground surveys. The contour lines can then be drawn for such low values of the magnetic field and at such a density that even weakly magnetized formations are revealed. In prospecting for nickel

ores, we have been able to increase the use of borehole three-component magnetic measurements thanks to improved computer-based interpretation methods (Hattula 1986).

## GEOCHEMISTRY

The most recent applications of geochemistry involve regional till surveys by the Geological Survey of Finland; the use of crawler-based sampling units, which move easily across the terrain, for taking rock chips and drilling core samples from the bedrock surface covered by overburden; and some lithogeochemical methods developed for the exploration of certain ore types.

Of the systematic regional geochemical surveys undertaken by the Geological Survey of Finland on the basis of till, stream sediment, and heavy mineral sampling, the till maps compiled for various elements at a scale of 1:100 000 and with a sample density of one composite sample/4 km² have found the widest application in exploration. The extensive mapping of potential ore-bearing zones by sampling till at a density of 15 to 20 stations/km² is on the increase.

As shown by recently discovered ore deposits, the lithogeochemical methods developed for the exploration of Outokumpu-type Cu-Co-Zn ores (Huhma and Huhma 1970) and Ni-Cu ores (Häkli 1963, 1971) have turned out to be the most useful.

Lithogeochemical exploration for Outokumpu-type Cu-Co-Zn ores seeks to pinpoint the Ni, Co, Cu, and Ni/Co anomalies that are typical of the rock types and rock groups of the formation in the lithological association that hosts the Cu-Co ores, and which are outside the range of normal variation deduced from comprehensive drill core data.

In lithogeochemical exploration for nickel ores, the primary mafic silicates (such as olivines, orthopyroxenes, augites, and amphiboles of the mafic and ultramafic rocks), are assayed for nickel and iron. The chalcophile cations Ni, Co, Cu, and Zn of the coexisting sulphide phase are analyzed by AAS (atomic absorption spectrometry) and sulphur by a sulphur determinator. The major elements that determine the total compositions of the rocks are analyzed by XRF (x-ray fluorescence).

The use of lithogeochemistry in nickel exploration has two purposes: first, to provide information about the areal distribution of mafic-ultramafic rocks whose geochemical properties suggest the possible presence of sulphide nickel ores; and second, to furnish data pertinent to the geochemistry, differentiation, and crystallization history of individual mafic intrusions and thus to delineate the potential parts of the bodies to which exploration activities in conjunction with other methods could be directed.

## GEOPHYSICS AND GEOCHEMISTRY OF OREBODIES

### OUTOKUMPU-TYPE COPPER-COBALT OREBODIES, EASTERN FINLAND

#### General

The Cu-Co orebodies discovered in the region are associated with a lithological complex made up of serpentinites, skarns, carbonate rocks, and quartzites. The outer zone of this rock association in contact with the surrounding mica schists is commonly occupied by black schists.

The locations of the Cu-Co orebodies of Outokumpu, Vuonos, and Kylahti (an orebody discovered in 1985 at a depth of 500 to 600 m, some 15 km northeast of Vuonos) are marked on the gravimetric map in Figure 73.2. The Outokumpu zone, which does not clearly show up on the gravimetric map, can be identified on the gray-tone images of the aeromagnetic low-altitude survey data (see photo in Figure 73.2). Until the early 1980s, exploration activities were directed from Vuonos northeast toward Haapovaara in accordance with the trend of the magnetic and slingram anomalies.

The Outokumpu orebody, averaging 3.80 percent Cu and 0.20 percent Co, was discovered in 1910. The orebody has a total length of 4 km; it crops out at the extreme northeastern end but tapers off to the southwest at a depth of 150 m.

#### Vuonos Orebody, Outokumpu Area, Eastern Finland

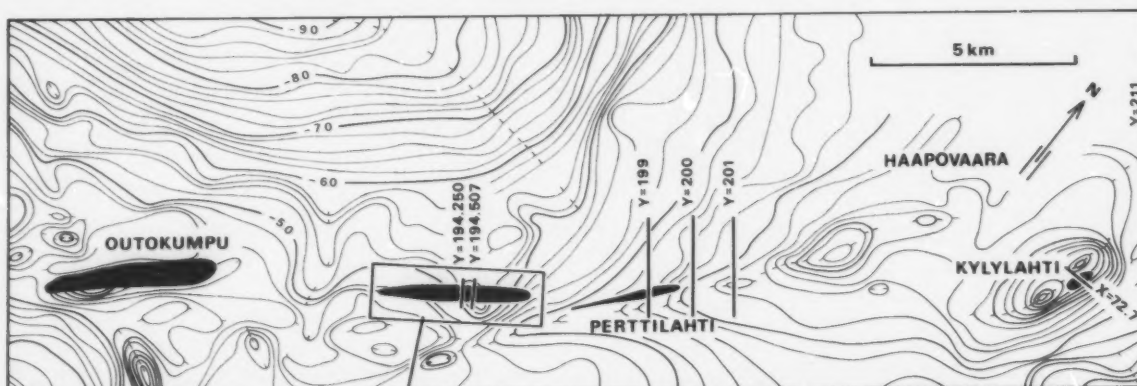
The Vuonos orebody, located about 6 km northeast of Outokumpu, was found in 1965. The orebody, which has been mined out, was about 3.5 km long. The southwestern end was at a depth of about 60 m and the northeastern end at about 200 m. Because of its horizontal position and great depth, the high density and conducting orebody could not be located using geophysical methods. The anomalies produced by the country rocks camouflaged the weaker anomaly produced by the ore (Ketola 1979).

A lithogeochemical method played a decisive role in the discovery of the Vuonos orebody. The method is based on the normal and anomalous abundances of Ni, Co, and Cu, on the Ni/Co ratios in various rocks and rock groups, and on the diagrams for Ni-Co, Cu-Co and Cu-Co-Ni variations as deduced from comprehensive drill core analytical data.

The changes that the Cu-Co ore produces in the normal element concentrations of the rocks result in an elevated Co content. Therefore, the Ni/Co ratio gradually decreases in line with the increase in the influence of the ores. In the anomalous serpentinites, the Ni/Co ratio is less than 15:1. A large orebody in a serpentinite-quartzite environment shows Ni/Co ratios of 2:3 to 1:3. Anomalous quartz-



AIRBORNE MAGNETIC GREY TONE MAP

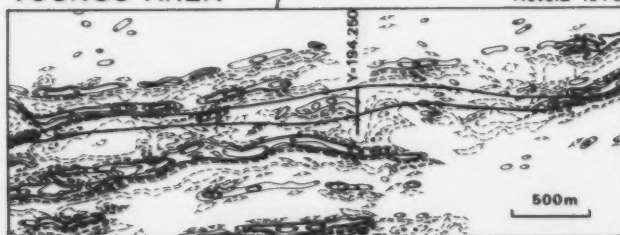


GRAVITY MAP

Contours: 0.2, 0.4, 0.6 mgal  
 Surface projection of orebody

VUONOS AREA

Ketola 1979



SLINGRAM MAP (Real component)

Contours:  $\pm 4, 8, 16\%$  etc.  $f=1775$  cps  $a=40$  m

Figure 73.2. Geophysical maps of the Outokumpu area.

ite-skarn-dolomite zones exceptionally rich in Co have been encountered in areas where Cu-Co ores occur. These anomalies are not always directly associated with the ores but they may occur as separate zones in serpentinite-quartzite assemblages.

The first indications of Cu-Co ore in the Vuonos area were the high Co and Cu contents and the low Ni/Co values noted in 1964 in the quartzite-skarn zones intersected by holes DH-186 and 187 drilled into profile  $y = 194.507$  back in the 1950s.



The anomalous intersections are marked on the geological cross-section in Figure 73.3, and on the Ni-Co and Cu-Co diagrams illustrating the normal variation in the contents of these elements in Outokumpu-type rocks. Figure 73.3 gives the variation in Cu content and the Ni/Co ratio in drillhole DH-186. It also shows that the serpentinite intersected by the drillhole has an anomalous Ni/Co ratio of 10:1. The Vuonos orebody, in which the Ni/Co ratio is 2:3, was discovered with hole DH-217, drilled into cross-section y = 194.250. In this cross-section, also, there is an anomalous quartzite-skarn formation in the hanging wall of the ore. The geophysical and petrophysical section of y = 194.250 was published by Ketola (1979).

### Kylylahti Orebody, Outokumpu Area, Eastern Finland

In the mid-1960s, at the time of the discovery of the Vuonos orebody, the computational interpretation of geophysical anomalies with programmable calculators and computers was feasible to only a limited extent. In the early 1980s, we decided to interpret tentatively the old gravimetric survey data measured between Vuonos and Kylylahti. Shown in Figure 73.4 are the results of the interpretation of three profiles, y = 199, 200, and 201, spaced 1 km apart. The locations of the profiles are marked in Figure 73.2.

The interpretation of profile y = 199 shows that the anomaly curve deduced from outcropping models heavier than the mica schist environment ( $\delta = 2.75$ ), and based on information from the shallow holes previously drilled in the area, fits poorly with the measured curve in the middle of the profile. If, however, a "blind" (i.e. concealed) lithological formation heavier than the environment ( $\delta = 2.93$ ) is placed in the middle of the interpretation profiles at a depth of 400 to 1200 m, the measured and calculated curves fit each other well. The existence of this formation (which turned out to be dense rocks of the Outokumpu Formation) was established by drilling first on profile y = 200 and then on other profiles northeast of Vuonos. The drilling indicated that the Outokumpu-type rocks form a fold. The blind formation, which is heavier than its environment, is located at Vuonos, in the western limb of the fold. Northeastward, toward Kylylahti, the centre of gravity of the heaviest portion shifts to the eastern limb of the fold structure, in contrast to the trend of the magnetic anomalies, which indicate the surficial parts of the zone. The intersections in the deep drillholes are compatible with the outcome of the interpretation model particularly with regard to the hanging wall contact (Rekola and Ahokas 1986).

The great depth of the formation made it impossible to check the continuation of the blind formation from Vuonos to Kylylahti. However, this model

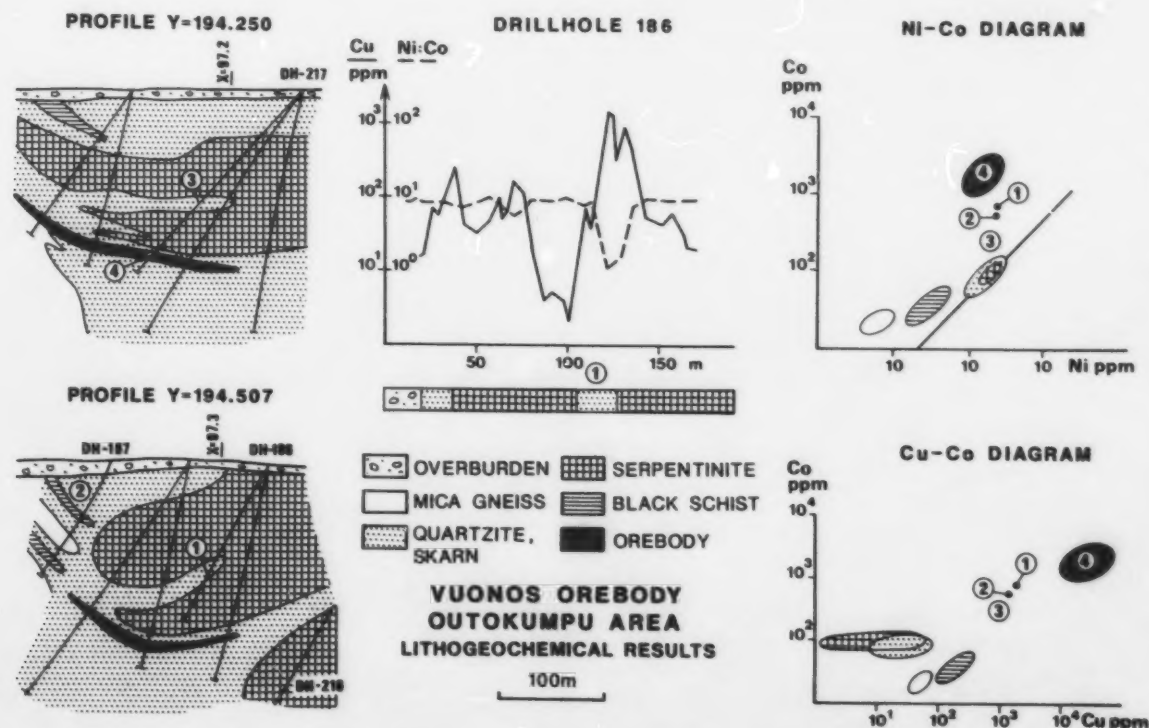
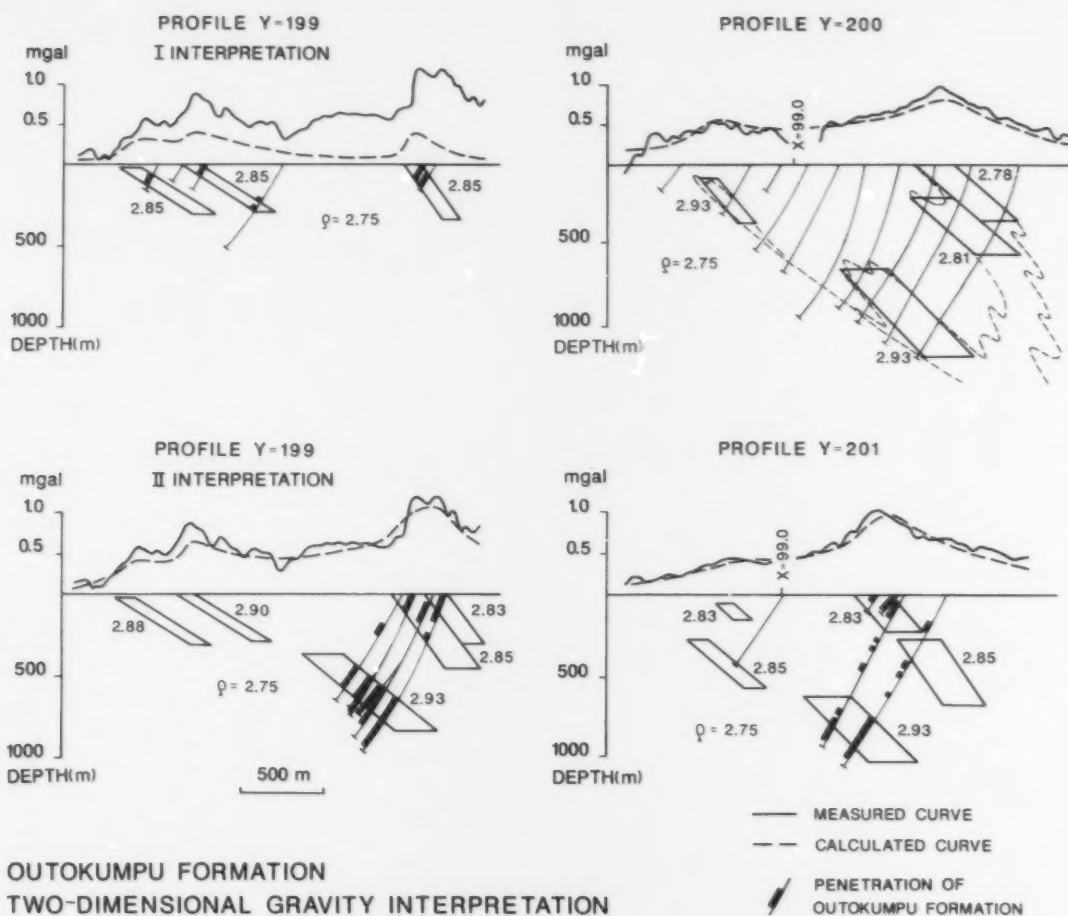


Figure 73.3. Use of lithogeochemical results in the discovery of the Vuonos orebody.





## OUTOKUMPU FORMATION TWO-DIMENSIONAL GRAVITY INTERPRETATION

Figure 73.4. Interpretation of gravity data between Vuonos and Kylylahti in the Outokumpu area.

led to the start of drilling at Kylylahti, where a big formation of Outokumpu-type rocks crops out. At an early stage of the drilling, the roughly 2 km long ribbon-like Perttilahti Cu-Co mineralization was located at a depth of about 700 m northeast of Vuonos.

Thin Cu ore intersections in the surficial parts of the Kylylahti Formation, and the anomalously high Co contents encouraged us to drill deep holes. These exhibited lithogeochemical anomalies characteristic of Co-Cu ores, and at a depth of 500 to 600 m we encountered high-grade ore, assaying 2.8 percent Cu and 0.4 percent Co. As indicated by the Ni-Co and Cu-Co diagrams in Figure 73.5, the quartzite-skarn zone shows anomalous values in the environment of the orebody. Closer to the surface, parallel to the axis of the orebody rather than transverse to it, the anomalies seem to be more distinct.

## NICKEL-COPPER OREBODIES

### General

Exploration for nickel ores proceeds stepwise. First to be mapped are the parts of the mica schist belts in which the composition of the sediments and the migmatization caused by typical metamorphic-tectonic events are similar to those encountered in the environment of known ore deposits. The results of regional till geochemical surveys undertaken by the Geological Survey of Finland for use in delineating the areas of mafic bodies are increasingly being made available.

Single mafic bodies can be located using principal component analysis with subsequent colour compositing of airborne geophysical low-altitude survey data, and magnetic and gravimetric survey data. For the location of larger mafic bodies gravimetric sur-

LITHOGEOCHEMICAL RESULTS  
PROFILE X-72.7

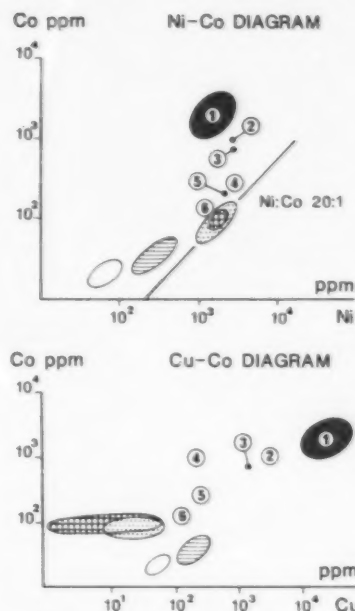
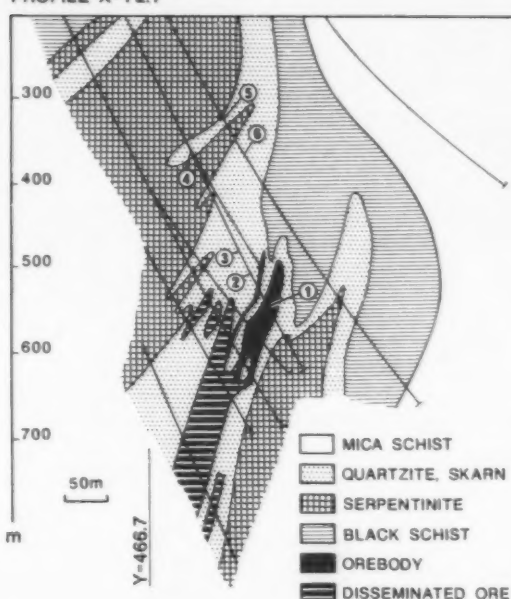


Figure 73.5. Use of lithogeochemical results in the discovery of the Kylylahti orebody, Outokumpu area.

veys are conducted on a coarse, irregular grid with a density of 4 to 6 survey stations/km². Gravity surveys are well suited to areas submitted to exploration for mafic bodies (such as gabbros and peridotites) that are heavier than the enveloping mica gneiss. Serpentinization lowers the density of peridotites, making it difficult to locate serpentine peridotites in areas with a marked variation in overburden thickness. However, serpentinized peridotites can often be detected with magnetic measurements.

Potentially nickel-bearing mafic bodies are detected lithogeochemically either by sampling the surface of mafic bodies through the overburden, or by analyzing drill cores. The outcome of surface samples is not always explorationally reliable owing to the layered structure of mafic bodies, which means that the ore-potential layer does not necessarily crop out. Lithogeochemical studies on drill cores play a key role in locating ores in mafic formations or the offset ores outside them.

Figure 73.6 gives the results of a regional till survey conducted in the Vammala area, where an economic nickel ore deposit was discovered in 1961. On the basis of the Ni and Cr anomalies in till, areas can be delineated where mafic bodies favourable for the occurrence of Ni ores are embedded in migmatites. PCA colour composites of the low-altitude airborne magnetic, EM real and EM imaginary component data made and interpreted by Aarnisalo (1984) cover part of the area (see Plate 73.1 in Colour Folio near back of book). The green or blue-green

anomalous hues on the image have enabled us to locate several formations of Ni explorational interest, e.g. the mafic body that hosts the Vammala Ni-Cu ore. The pyrrhotite-bearing black schists produce long, dark anomalies on the PCA colour composite map, thus enhancing the structural-geological interpretation.

#### Sotka Orebody, Vammala Ore Deposit, Southern Finland

This Ni-ore deposit is located in an intrusion; is composed of at least three layers that rest one on top of the other; and is surrounded by mica gneiss ( $\delta = 2.75$ ,  $k < 500$ ) (Figure 73.7). The lower and upper layers are ultramafic and the middle one is hornblenditic ( $\delta = 3.0$ ,  $k < 2000$ ). The uppermost layer is composed of serpentinized peridotite ( $\delta = 2.6$  to  $3.0$ ,  $k = 5000$  to  $15\,000$ ), causing magnetic anomalies. The lowest ultramafic layer, which contains all the ores of deposit, is mainly peridotite ( $\delta = 2.6$  to  $3.0$ ,  $k < 15\,000$ ). The petrophysical parameters of the nickel-bearing peridotite are of the same order of magnitude.

It was not until during mining, started in 1978, that underground drilling located the high-grade Sotka orebody. The orebody had remained between the two profiles drilled from the surface, and, of the two holes drilled from above it, one was too shallow (DH-64), and the other (DH-65) missed it altogether. The offset ore, which is clearly outside the mafic formation, cannot be detected with magnetic

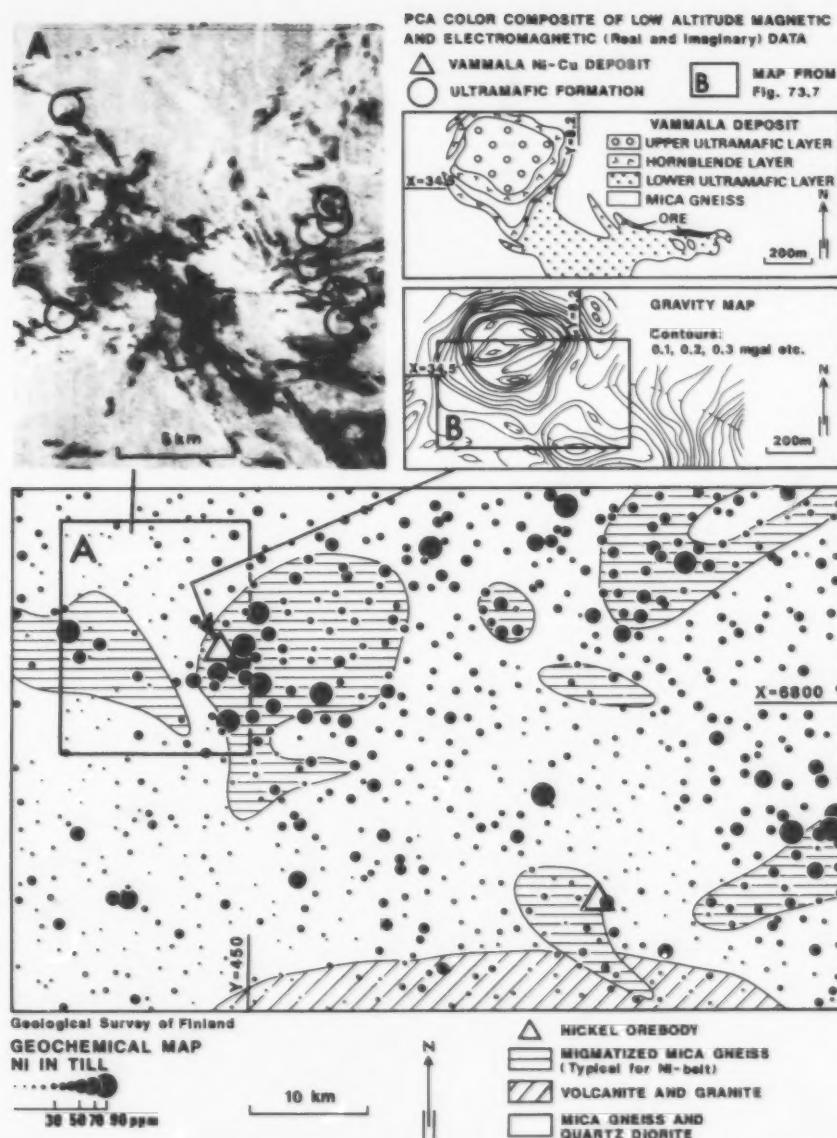


Figure 73.6. Combination of geological, geophysical and geochemical data in areal exploration of nickel-copper orebodies in the Vammala-Kylmäkoski area. To view PCA colour composite in colour, see Plate 73.1 in Colour Folio near back of book.

or gravimetric survey data. The shallow positive gravity anomaly on profile  $y = 8.2$  is mainly due to the fringe effect of the hornblendite layer. The hornblendite layer causes a strong positive anomaly on profile  $x = 34.5$ . The discovery of the Sotka orebody demonstrates how difficult it is to locate offset ores, because holes are generally drilled into a mafic formation or its contact zones. The geophysics and petrophysics of the Vammala orebody were described by Ketola (1982).

#### Enonkoski Orebody, Enonkoski Area, Eastern Finland

The Enonkoski ore deposit was discovered in 1980 as a result of two exploration campaigns conducted in the area in the 1960s and early 1970s. During the second stage of exploration, low-grade Ni mineralization was located and exposed at the eastern end of the mafic formation. It was intersected with about 30 drillholes. The geophysical results available from the

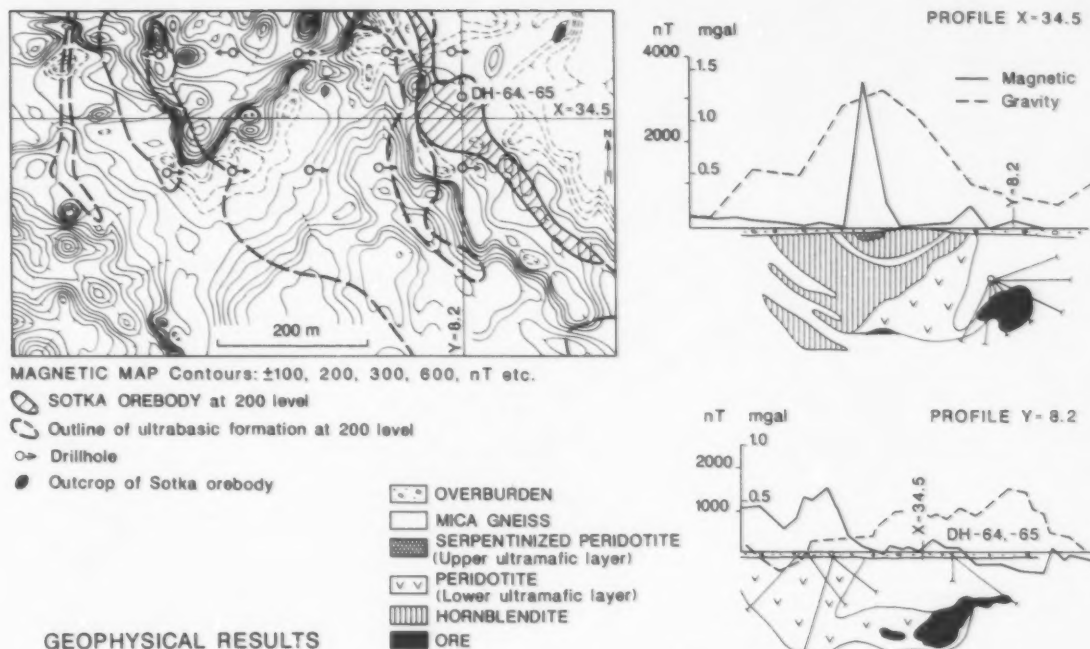


Figure 73.7. Geophysical results of the Sotka orebody of the Vammala ore deposit.

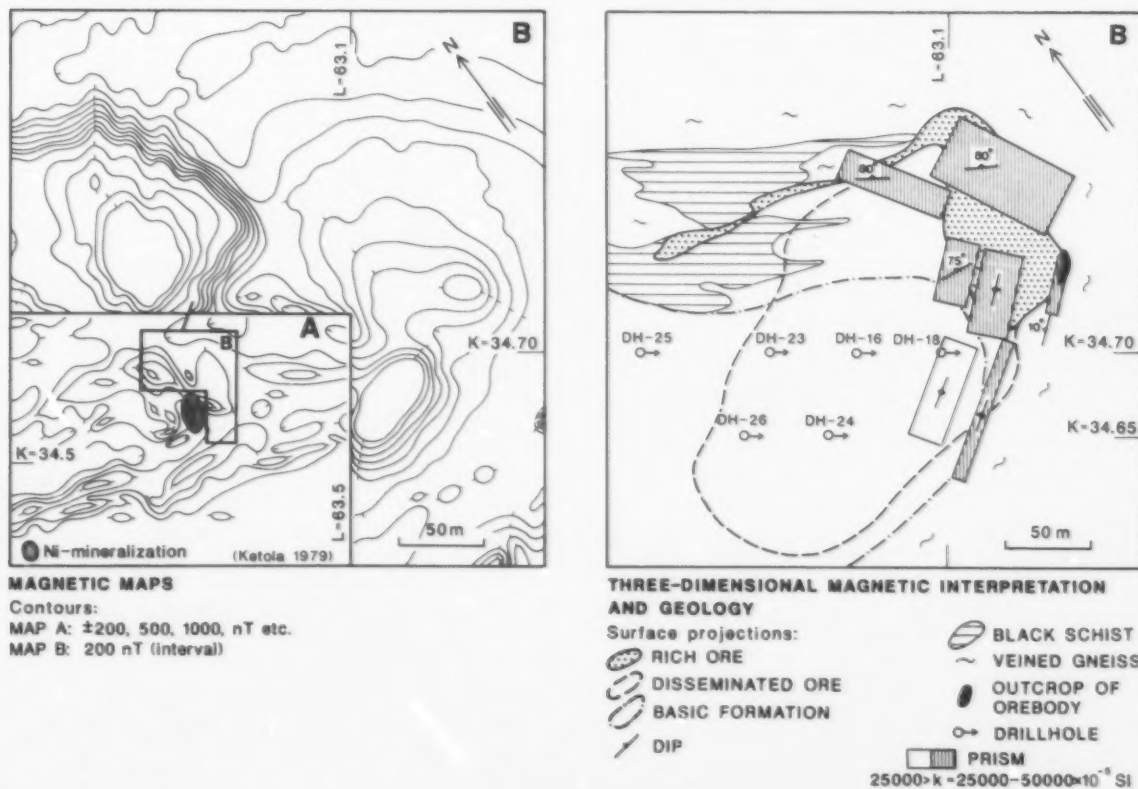


Figure 73.8. Three-dimensional interpretation of magnetic data over the Enonkoski orebody.



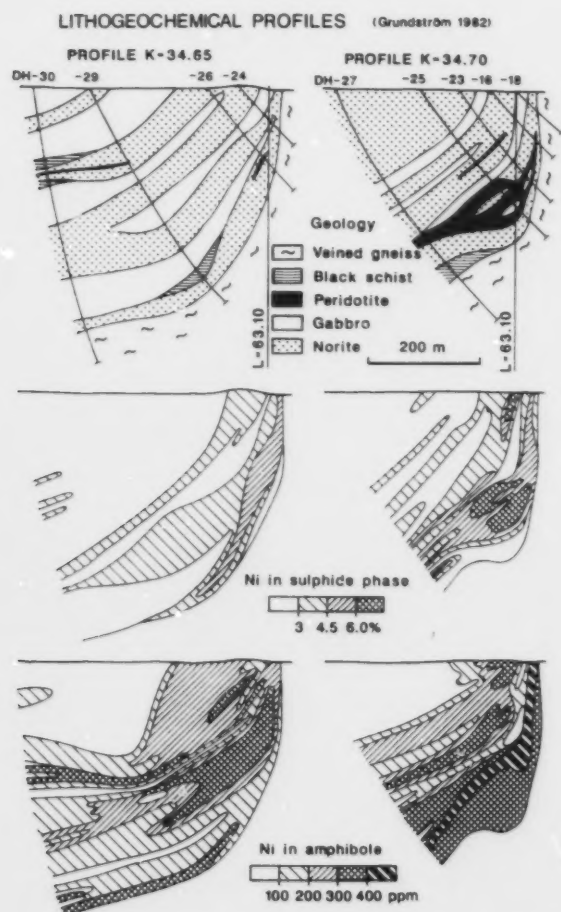


Figure 73.9. Geological and lithogeochemical cross-sections K = 34.65 and K = 34.70 of the Enonkoski orebody.

area in the early 1970s were published by Ketola (1979). The magnetic map (A) is shown in Figure 73.8.

In the lithogeochemical data on the drill cores, (some of which are shown in Figure 73.9), the Ni content in silicates, the MgO content, the Ni content in sulphide phase, the total Ni content, and the direction of differentiation of the lithological units, all indicate that the northeastern margin of the mafic formation has ore potential (Grundström 1980, 1982). The Enonkoski intrusion, which is surrounded by migmatitic mica gneiss, consists of a differentiation series ranging from peridotites to quartz diorites.

A magnetic survey was conducted on a 10 m grid on a bog northeast of the low-grade mineralization in an area which lithogeochemistry suggested was of interest. The resulting map (B), with dense contour lines, and the interpretation based on the prism models are shown in Figure 73.8. The inter-

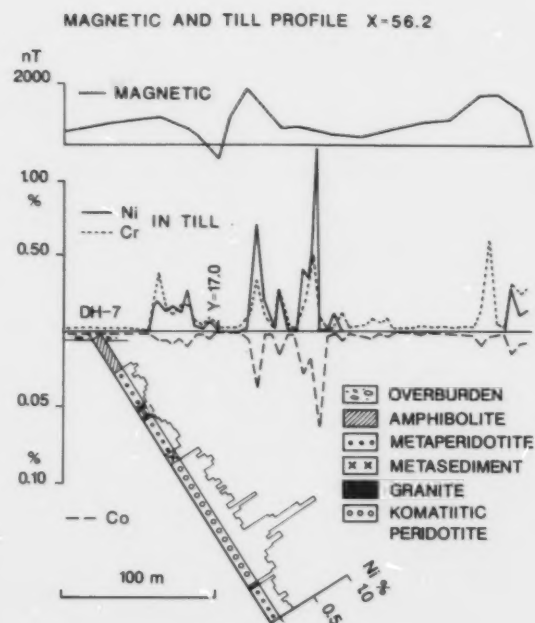


Figure 73.10. Combination of geophysical and geochemical data from profile X = 56.2 in the Pulju area.

pretation gave high susceptibility values to prisms whose upper face at the southern end of the interpretation model is at a depth of 10 m and at the northern end at approximately 80 m. The interpreted susceptibility values are about the same as those measured for the orebody from drill cores. About ten years after the second exploration stage, the holes drilled from the bog for checking the magnetic anomaly intersected a high-grade ore with a small subcrop, some 100 m from the low-grade mineralization.

#### Pulju Area, Northern Finland

Profile x = 56.2 from the Pulju area in Figure 73.10 illustrates the use of till geochemistry in the ranking of geophysical anomalies. On the profile, at the site of the positive magnetic anomalies, there are well-correlating Ni and Cr anomalies in till, indicating the location of the subcrop of the peridotite body intersected by drillhole DH-7. Some of the Ni-Cr anomalies also correlate strongly with the Co values in till. The analytical data on the drillhole show that the highest Ni values in the basal part of the peridotite, deduced as being komatiitic from the chemical composition, are superimposed on the Co anomalies. Therefore, the well-correlated Ni and Cr contents indicate the location of an ultramafic formation, and the Co anomalies the site of an explorationally interesting sulphide mineralization. The susceptibility of the komatiite increases along with the increase in the degree of serpentinization.

## ZINC-COPPER OREBODIES

### Rauhala Orebody, Ylivieska Area, Western Finland

An anomalous point in the regional till survey conducted in 1979 at a density of 10 stations/km² showed a Zn content of 530 ppm in the weathered bedrock (Iisalo and Salmiinen 1987). This find prompted checking sampling in 1983, which was carried out in the Rauhala area in several stages (Figure 73.11). The samples taken from the weathered bedrock in the environment of the anomalous point during the first stage exhibited high Zn values of 500 to 3200 ppm. The next stage, which led to the discovery of the Rauhala Zn-Cu ore deposit by the Geological Survey of Finland, was directed farther south to check the magnetic and negative slingram anomalies. The pyrrhotite-rich Zn-Cu ore embedded in sericitized mica gneiss contains 6 percent Zn and 1.7 percent Cu, and is highly conductive. Location of the subcrop of the orebody by means of slingram survey was only partially successful due to interference from a power line. The negative slingram anomaly west of the subcrop had been attributed to black schist before the discovery of the ore. Geochemical studies show that the anomalous sample had been taken from the weathered bedrock anomaly caused by the ore. The anomaly continues very distinctly northwards along the strike of the subcrop.

The depth extensions of the sheet-like orebody, which dips gently east-northeast at an angle of 30° to 35°, can be traced in areas where power lines and the fringe effects of the orebody do not interfere with electromagnetic multifrequency and TEM measurements. The location of the orebody on the

profile a-b was interpreted reliably (Fargas 1986) from the Maxi-Probe multifrequency EM sounding survey data, which had been measured jointly by ELGI and the Mid-Finland regional office of the Geological Survey of Finland.

## PGE OREBODIES

### General

A discontinuous belt of early Proterozoic layered intrusions about 300 km long extends from Tornio, on the Swedish border, eastwards to the Soviet border. The belt, in which ores of Cr (Kemi), Fe-Ti-V (Mustavaara), Ni-Cu, and PGE occur, comprises altogether about 20 exposed intrusive bodies varying in length from a couple of kilometres to almost 30 km. The layered intrusions are usually divided into three principal units: the marginal series, the layered series subdivided into various megacyclic units, and the granophyre.

PGE mineralization is encountered in the layered intrusions in two geological positions: close to the basal contact, and within the differentiation sequence. Marked PGE mineralization has formed on the boundaries of the megacyclic units wherever the magma pulses representing the units differ in composition. The megacyclic units differ in Ti/Cr ratio, and in Cr values. The ultramafic zones poor in Cr, which are located in the megacyclic zone above the Cr-rich basal part, have the potential for containing PGE.

Four types of PGE mineralization have been met with in the layered intrusions in the Narkaus area. The offset mineralization, in which palladium usually predominates over platinum (Pd/Pt ratio is approximately 10) and which may have a significant Cu grade, occurs in the rocks of the granite gneiss com-

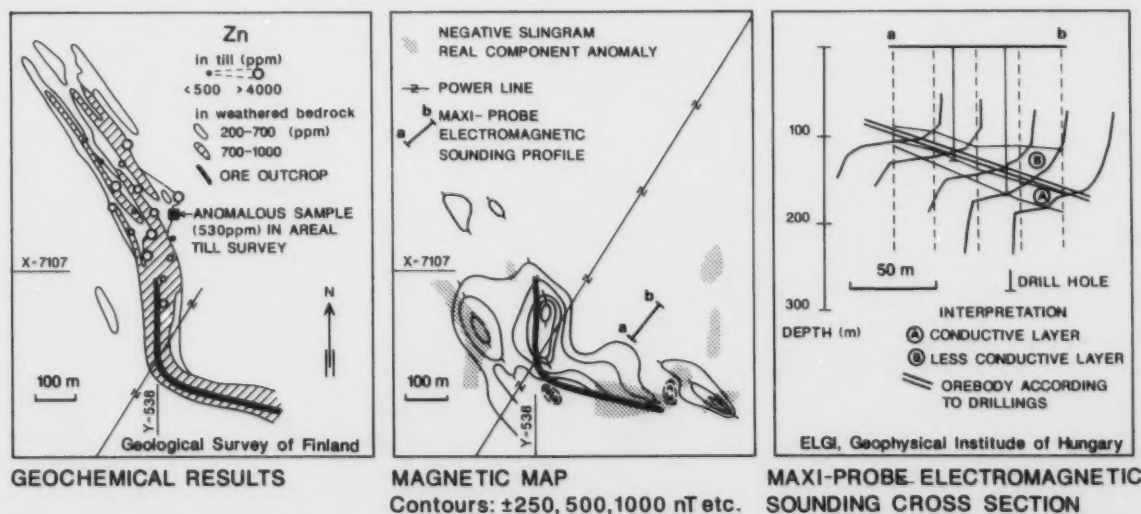


Figure 73.11. Combination of geochemical and geophysical data in the discovery of the Rauhala orebody, Ylivieska area.

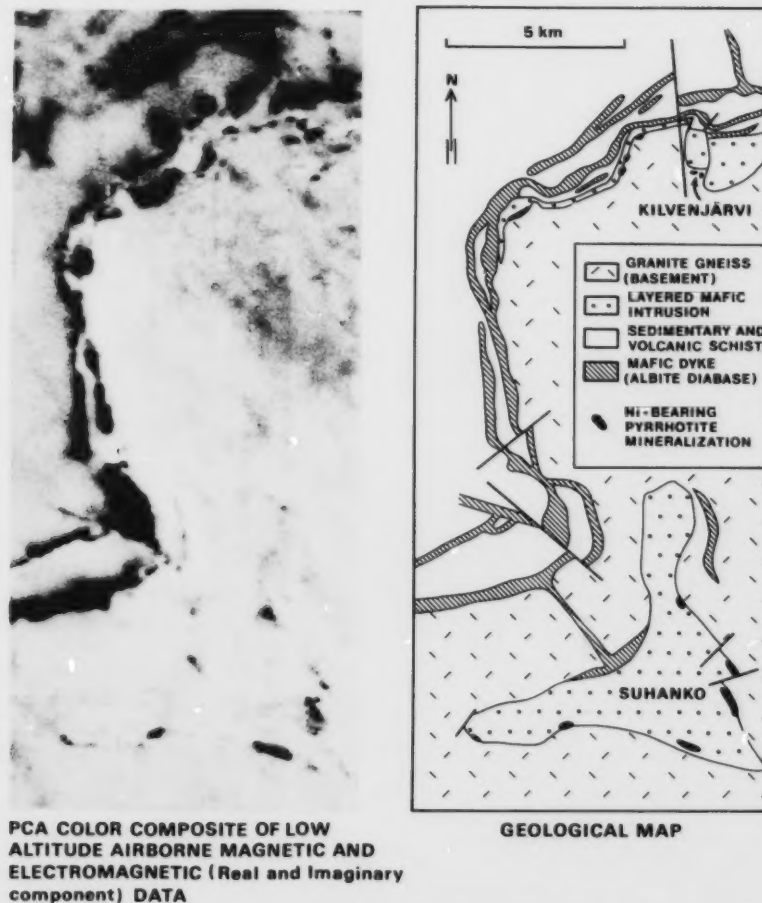


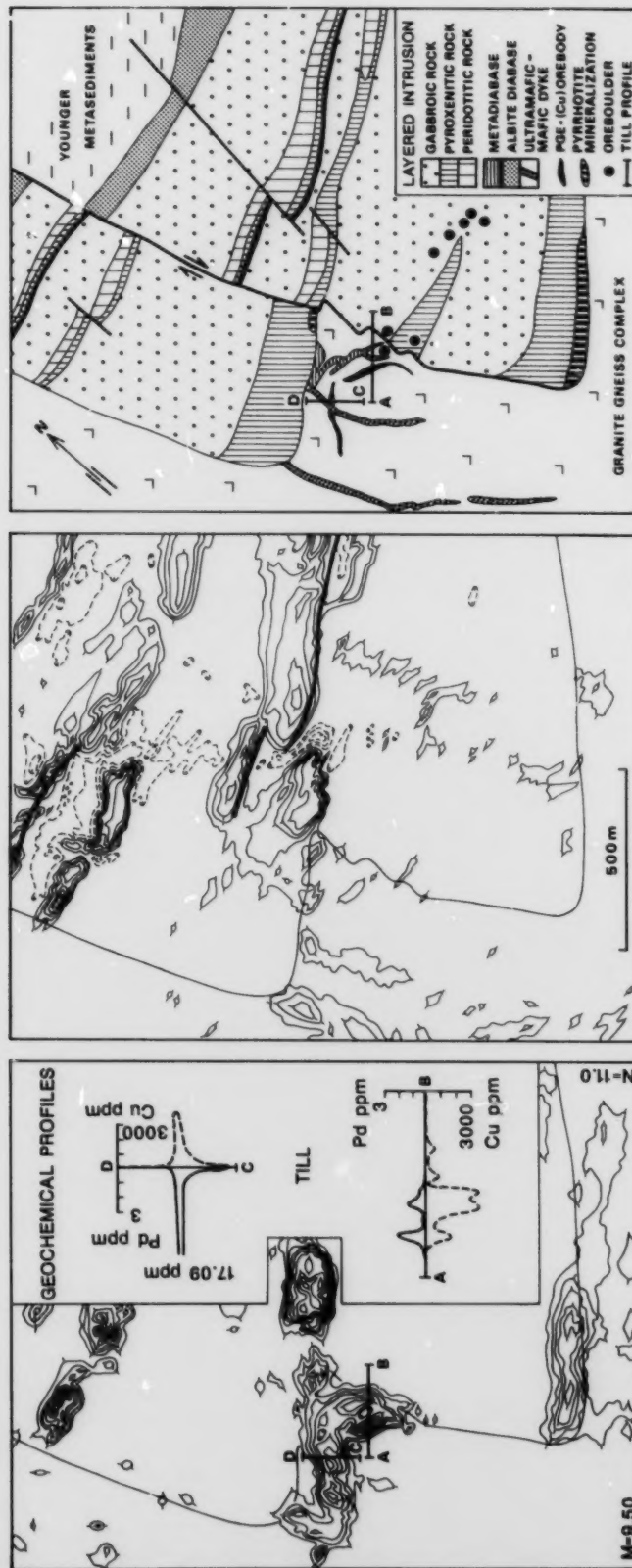
Figure 73.12. Use of PCA colour composite of airborne data in areal exploration of sulphide and PGE orebodies in the Narkaus area. To view PCA colour composite in colour, see Plate 73.2 in Colour Folio.

plex outside the layered intrusion. Massive pyrrhotite ores with low Ni, Cu, and precious metal values are met with in the basal contact of the layered intrusions.

PGE mineralization has also developed in the marginal zone of the layered intrusion, in the ultramafic unit high in the differentiation sequence, and in the underlying gabbros. Apart from the offset type of copper-bearing PGE ores (Kilvenjärvi-type), the ones of greatest explorational interest are those located in the ultramafic rocks of the marginal zone of the layered intrusion, and here and there partly in granite gneiss basement (Konttijärvi-type). However, these orebodies, which can be up to 20 m thick, are of fairly poor quality ( $\text{Pd/Pt}$  = approximately 3.5). The PGE mineralization that occurs in the upper parts of the sequence is no more than a few metres thick but it is persistent, extending parallel to the strike throughout the whole intrusion. For

example, in the Penikat layered intrusion it is about 23 km long (Alapieti and Lahtinen 1986).

The discovery of the Kemi chromite ore was followed by prospecting for Cr and Ni-Cu ores in the zone of the layered intrusions in the 1960s and 1970s. However, no economic ore deposits were found. The PCA colour composite of the low-altitude airborne magnetic and electromagnetic data on the Narkaus area (Figure 73.12 and Plate 73.2) shows that the layered intrusions, e.g. the Suhako intrusion, cannot always be located from the magnetic anomalies. Being good conductors, however, the nickel-bearing pyrrhotite mineralization in their contacts manifests itself clearly as red anomalies on the PCA colour composite map. On account of their high susceptibility, the albite diabases emplaced in the contact of the schists with the granite gneiss basement constitute a good geological marker horizon for exploration. The lack of graphite schists has considerably facilitated geophysical and geochemical exploration in the area.



GEOLOGICAL MAP

MAGNETIC MAP  
Contours:  $\pm 100, 200, 400, 800, 1600$  nT etc.

IP-MAP (CHARGEABILITY)  
Contours: 8, 12, 16, 20, 25, 30 mV/V etc.  
Dipole-dipole,  $n=4$ ,  $a=20m$

Figure 73.13. Comparison between geological, geophysical, and geochemical data from the Kilvenjärvi orebody, Narkaus area.



# Kilvenjärvi Orebody, Narkaus Area, Northern Finland

In the 1970s, a number of copper-bearing ore floats (Figure 73.13) were discovered in the Kilvenjärvi area, in the north of the Narkaus area (Figure 73.12). Geochemical studies established Cu anomalies in till northwest of the floats at the site where the orebody was later to be found. The area was submitted to high-frequency slingram measurements ( $f = 18\,500\text{ Hz}$ ). However, distinct anomalies were not detected and exploration was suspended.

It was noted in the course of the PGE studies that the ore floats contained appreciable PGE and that till showed strong palladium anomalies in addition to Cu anomalies. At the site of the till anomalies, which are superimposed by a strong IP anomaly, drilling indicated a PGE offset orebody composed of four lenses with local high Cu values. The peridotite zones in the sequence of the Kilvenjärvi intrusion exhibit magnetic and IP anomalies caused by magnetite. The magnetic anomaly disappears at sites where the peridotite grades into pyroxenite. Despite the faults, the magnetized peridotite zone can be used as a marker horizon when tracing the narrow sequences of PGE mineralization along the strike. This is feasible, particularly if the data allow the contour lines of the low intensity magnetic field to be drawn with such density that the weakly magnetized formations can be detected.

## Konttijärvi PGE Orebody, Narkaus Area, Northern Finland

The small Konttijärvi layered intrusion is located about 3 km northwest of the western end of the Suhanko layered intrusion (Figure 73.14). The peridotites, pyroxenites, and some of the gabbros of its marginal zone host a subhorizontal lens of disseminated sulphides rich in PGE and with some Ni and Cu. The two-peak IP anomaly on profile  $y = 54.4$  is caused by the joint effect of the magnetized peridotite and the PGE mineralization in its footwall. The location of its subcrop is clearly indicated by the Ni, Cu, and Pd anomalies in the till.

## GOLD OREBODIES

### General

Systematic large-scale exploration for gold was not conducted in Finland until the 1980s. Exploration is now under way in Proterozoic schist areas and Archean greenstone belts. During this rather short period, efforts have been rewarded with the discovery of a number of small gold occurrences. Some of them are in a geological environment where pyrrhotite-bearing graphite schists are not very abundant, and hence electrical methods can be used in direct exploration.

### GEOPHYSICAL AND GEOCHEMICAL RESULTS PROFILE Y-54.4

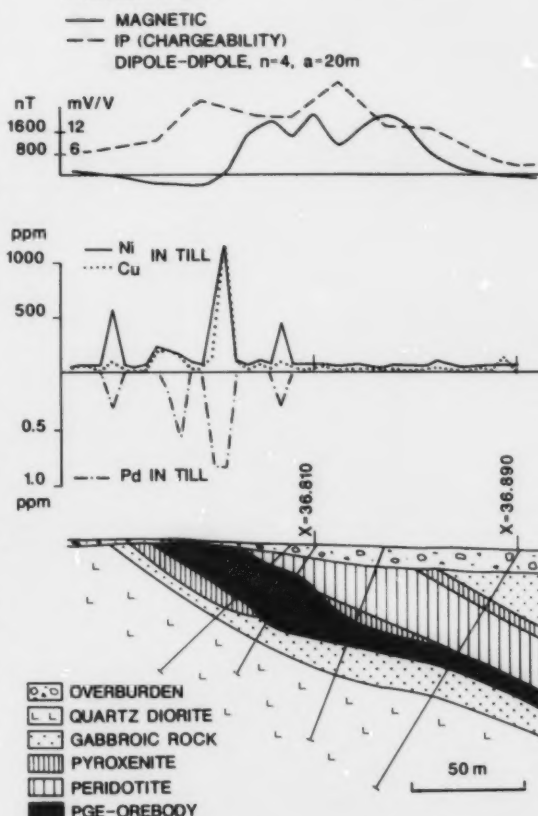


Figure 73.14. Comparison between geophysical and geochemical data from profile  $Y = 54.4$  from the Konttijärvi orebody, Narkaus area.

## Saattopora Orebody, Kittilä Area, Northern Finland

The Pahtavuoma copper deposit was discovered in the early 1970s. The geophysical results pertinent to the discovery were reported by Ketola (1979). The deposit is situated in a phyllite schist zone in the southern part of the Kittilä greenstone belt. The phyllites that host the orebodies are graphite-bearing and cause strong slingram and VLF-EM anomalies (Figure 73.15).

Geochemical heavy mineral and till surveys have been undertaken in the area in the 1980s, the former on a regional scale. The surveys have located a structurally deformed, metasomatically altered, potentially gold-bearing zone of ultramafic rocks on a different stratigraphic level in the schist belt. The zone includes the Saattopora gold orebody and a Cu mineralization found immediately east of it in the early 1970s (Figure 73.16).

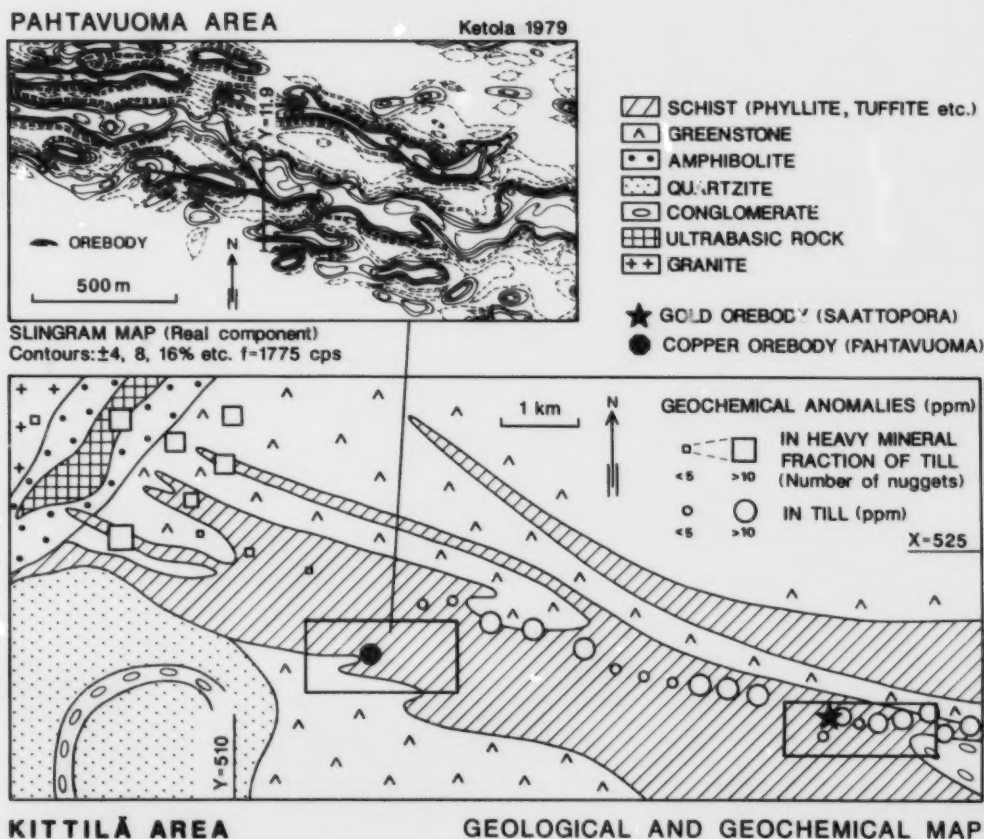


Figure 73.15. Use of geochemistry in areal gold exploration in the Kittilä area.

The gold ores occur in carbonatized and silicified talc-chlorite schists or, as at Saattopora, in the adjacent albite-rich rocks. The phyllites, which cause intense electromagnetic anomalies, often contain only small amounts of magnetite and do not show up on the magnetic map. The ultramafic rocks, on the other hand, which are relevant for the occurrence of gold ores, generally are magnetized. They give rise to Ni and Cr anomalies in the overburden and in the underlying weathered bedrock, which is the target of geochemical sampling.

The potentially gold-bearing zone, is shown distinctly by the anomalous gold values in the weathered bedrock marked on the VLF map with abundant anomalies. The first indications of the Saattopora gold ore were obtained when the re-analysed cores from the holes drilled in the early 1970s during exploration for Cu ores showed marked gold values.

Computational interpretation of the magnetic anomalies caused by the ultramafic rocks makes it possible to establish indirectly the dip of the gold-bearing albite rock formation adjacent to them, and

thus to determine the appropriate drilling direction. Two-dimensional magnetic interpretation of profile  $y = 517.75$  (Figure 73.17), which omits remanence, gives susceptibility  $k = 4000$  to  $14\,000$  for the talc-carbonate schist. The values are compatible with the susceptibilities measured *in situ* from the holes drilled into the profile. The values, which are marked beside the drillholes, also show the location of the albite rock formation.

#### Hattuvaara Gold Orebody, Ilomantsi Area, Eastern Finland

The Hattuvaara gold orebody occurs in a conglomerate (Figure 73.18), in a shear zone characterized by sericitization and tourmaline-bearing quartz veins at the contact between an intermediate volcanite and a greywacke conglomerate. The gold-bearing zone, which contains some pyrite, can be traced with IP measurements. A silicate iron formation, which occurs in the contact of the intermediate volcanite with a tonalite and acts as a distinct geological marker horizon, causes a weak magnetic anomaly and a weak IP anomaly.

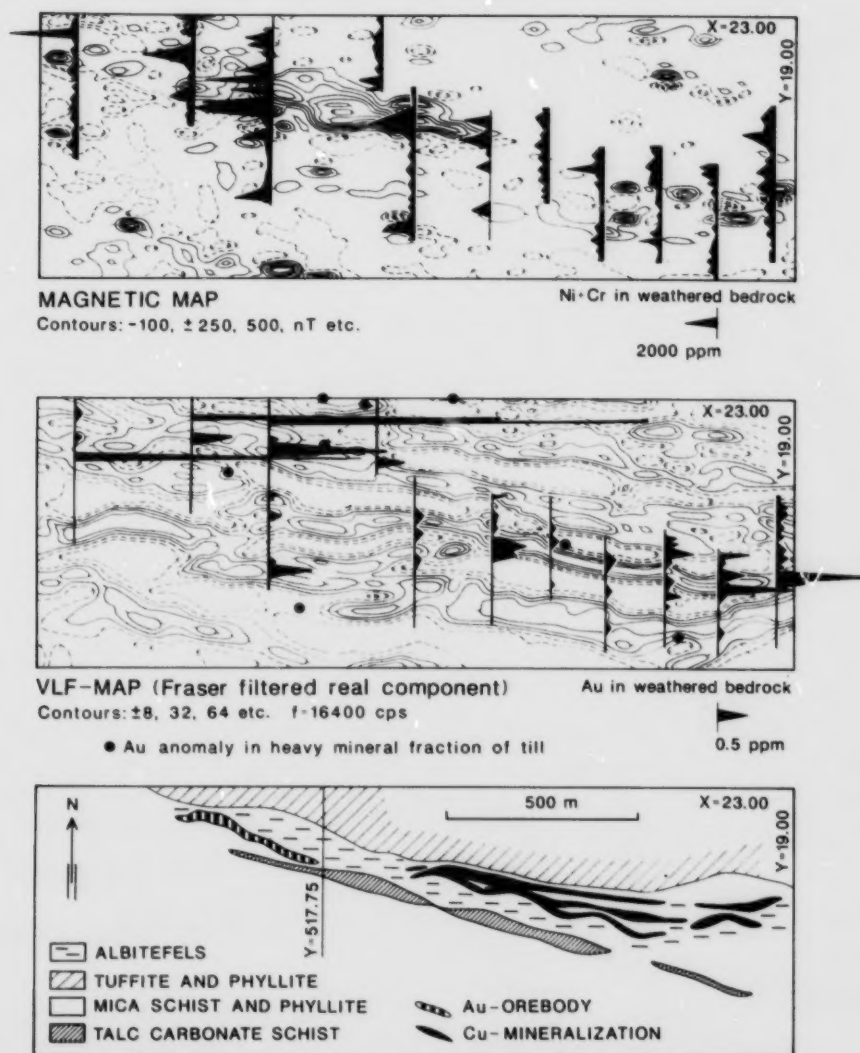


Figure 73.16. Combination of geological, geophysical, and geochemical data in the Saattopora orebody, Kittilä area.

## CONCLUSIONS

The discoveries of sulphide and precious metal ores described in this paper show that integrated application of geophysical and geochemical methods, in which the contribution of geochemical methods has increased in recent years, provides new prospects for explorationally difficult graphite schist areas, both those requiring deep exploration and those that have been explored in detail with older methods. The problem with deep exploration in particular, is its high cost and slowness, because we do not often have methods capable of guiding drilling directly to the ore. Exploration is somewhat simpler in areas with a low abundance of graphite schists.

The key factors in long-term exploration are the correct selection of survey areas and methods, and integrated interpretation of the data, a procedure in which the key factor is the human one (Ketola 1987).

## ACKNOWLEDGMENTS

I express my cordial thanks to the geologists, geophysicists, and geochemists involved in the exploration projects of Outokumpu Exploration, the recent results of which are described in this paper.

J. Lahtinen, Geologist, and E. Sandgren, Geophysicist, were responsible for the PGE surveys undertaken in northern Finland. R. Hugg, Geologist,

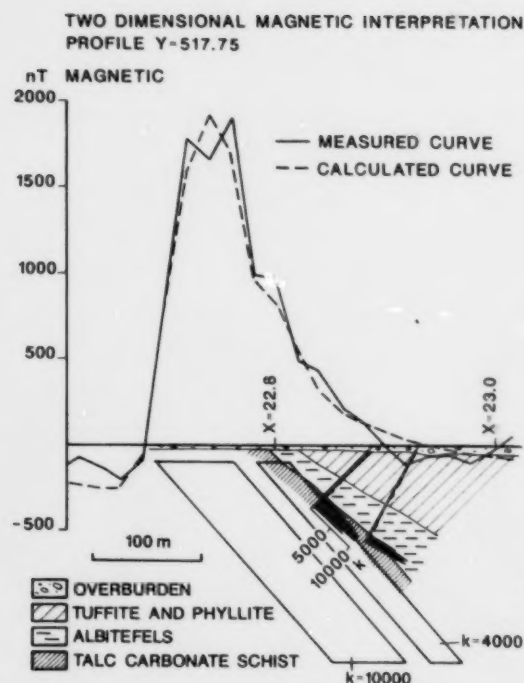


Figure 73.17. Interpretation of magnetic data from profile Y = 517.75 over the Saattopora orebody, Kittilä area.

and R. Pelkonen, Geophysicist, were responsible for the gold surveys. The geochemist on both projects was E. Ilvonen.

The geophysical interpretations of the Outokumpu and Enonkoski areas were conducted under the guidance of T. Ahokas, Geophysicist, whose personal contribution had a decisive impact on the success of the interpretations. I am also grateful to O. Inkinen, the Geologist in charge of surveys in the Pulju area, and to A. Hattula and T. Lehtonen, the Geophysicists in the Ilomantsi and the Vammala areas.

Thanks are also due to the Geological Survey of Finland, especially Professor J. Talvitie, R. Salminen, A. Ruotsalainen, E. Soininen and T. Jokinen, for permission to publish the data pertinent to the discovery of the Rauhala Zn-Cu orebody.

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## HATTUVAARA Au-mineralization Profile X= 77.70

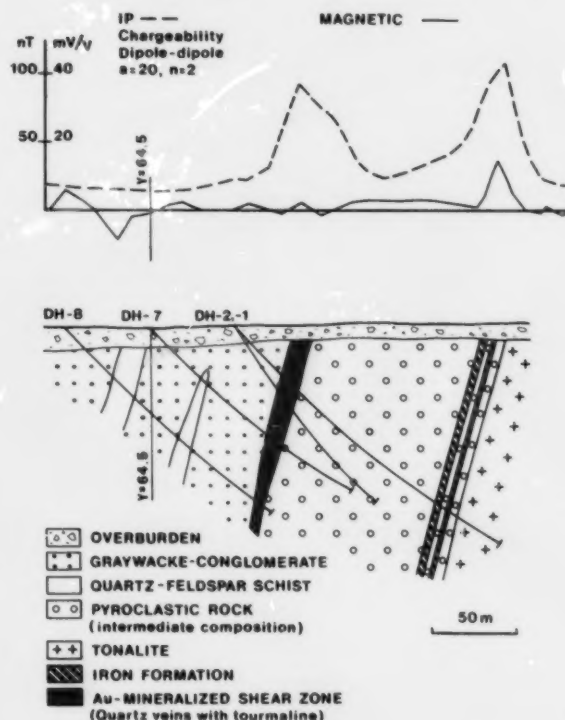


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# 74. The Casa Berardi Area: An Exploration Case History

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## ABSTRACT

The Abitibi Orogenic Belt of the Canadian Shield is a prolific host of base and precious metal deposits. Covering an area over 500 km in length in Ontario and Québec, the Abitibi Belt consists of a series of greenstone belts of Archean age. The known economic mineralization is often associated with major regional structural deformation zones with an easterly trend sympathetic with the Precambrian sedimentary and volcanic units which constitute individual greenstone belts. The Destor—Porcupine and Larder Lake—Cadillac Breaks are the main deformation zones in the south-central Abitibi and have several major mining camps associated with them.

The north-central Abitibi is relatively undeveloped due to the minimal outcrop and the high cost of exploration. However, in the last ten years the pace of exploration has increased dramatically partly due to the discovery of the Golden Pond and Estrades Deposits and the advent of flow-through share financing.

Much of this exploration has been concentrated in a sector of the north-central Abitibi known as the Casa Berardi area. Due to the extensive deep overburden cover, the geology of this region was initially interpreted primarily from airborne geophysical surveys. Initial ground investigation of selected targets consists of geophysical and reverse-circulation drilling programs. The evolution of the current exploration philosophy is described with the aid of case histories of the Golden Pond and Estrades Deposits which are approximately 20 km apart.

Evidence is presented in favour of the presence of a regional graphitic fault/shear zone, one to two metres wide and with an eastward trend, on both the Golden Pond and Golden Hope Properties. This regional fault is known as the Casa Berardi Fault on the Golden Pond Property and is always located within the suite of sediments and volcanics comprising the Golden Pond Sequence. The lithologic units within the Golden Pond Sequence have been subjected to mild deformation over several hundred metres about the Casa Berardi Fault. The term "Casa Berardi Deformation Zone" is increasingly being used to describe this area.

A reasonable assumption is that the Casa Berardi Fault on the Golden Hope Property is associated with an eastward extension of the Casa Berardi Deformation Zone. The width of the defor-

mation zone and whether it encompasses the Estrades Deposit cannot be determined with any certainty at present.

The width, intensity of deformation and currently inferred strike length of the Casa Berardi Deformation Zone are not as extensive as those associated with the Destor—Porcupine and Larder Lake—Cadillac Breaks. Nonetheless, significant economic mineralization has been found within the Casa Berardi Deformation Zone to date and, the authors believe, will continue to be found in the years to come.

## INTRODUCTION

The Abitibi Orogenic Belt of the Superior Structural Province of the Canadian Shield has historically been, and continues to be, one of the most prolific hosts for precious and base metal deposits in the world.

Covering an area over 500 km in length from the Kapuskasing High in Ontario to the Grenville Front in Québec, the Abitibi Belt comprises a number of greenstone belts of Archean sediments and volcanics which are intruded by various generations of felsic to ultramafic rocks (Figure 74.1).

Economic gold and base metal mineralization within these greenstone belts is often spatially related to, and possibly genetically associated with, regional structural features. For instance, in the south-central portion of the Abitibi Belt, the Porcupine Gold Area is located on the Destor—Porcupine Break while the Virginiatown and Val d'Or camps are sited on the Larder Lake—Cadillac Break. Both are major east-trending deformation zones which have been the subject of extensive exploration and development programs.

Until recently, exploration in the north-central Abitibi was hampered by difficult access and thick overburden. The intensity of exploration has increased dramatically over the last ten years as a result of: a) the construction of all-weather gravel roads for the logging and mining industries; b) the development of the Detour, Selbaie and Agnico-Eagle Mines (Figure 74.1); c) the delineation of the Golden Pond gold orebodies (1981 to 1986) and the polymetallic Estrades Deposit (1985); d) the discovery of a number of showings where potentially economic mineralization has been intersected; and e) the advent of flow-through shares which provided a



Figure 74.1. The Abitibi Greenstone Belt.

mechanism to raise sufficient finances for high-cost, high-risk exploration programs.

This paper deals with a region within the north-central Abitibi Greenstone Belt known as the Casa Berardi area, so named following the initial Golden Pond discovery by Inco Limited in Casa Berardi Township in 1981.

The area contains minimal outcrop and is generally flat and swampy or heavily forested so that initial knowledge of the geology relies heavily on interpretation of numerous private sector and government-sponsored airborne geophysical surveys (Figure 74.2).

The Casa Berardi area is interpreted to be underlain primarily by Early Precambrian intermediate to mafic volcanics. Felsic volcanic flows and pyroclastics tend to occur as relatively discrete, thin units interbedded with the mafic volcanics. Sedimentary or tuffaceous units, generally with eastward trends, extend over tens of kilometres and are accompanied by graphite, argillite and sulphide or oxide facies iron formations.

The major intrusives in the region are Early to Middle Precambrian granodioritic-monzonitic or tonalitic-dioritic rocks. Late Precambrian diabase dikes trend north-northeast to northeast.

During the late 1960s and early 1970s, several mining companies were attracted to this sector of the Abitibi for its base metal potential. The exploration approach at that time was to carry out regional airborne surveys, sometimes of complete greenstone belts, and then select smaller areas for further evaluation.

The exploration philosophy in the region has changed over the last two decades as a result of new technology in geophysical instrumentation, developments in exploration techniques and the shift in emphasis from base to precious metals.

The thick glacial overburden cover is of variable conductivity and bedrock topography is often severe, with overburden depths typically varying from 10 to 100 m. Initial ground follow-up exploration in areas selected from the airborne surveys is therefore confined mainly to geophysical and reverse-circulation drilling surveys.

The standard approach at present is for total field magnetometer and horizontal loop electromagnetic surveys to be completed over a large area so that lithologic and structural information can be derived. Favourable conductive horizons are further screened by reverse-circulation drilling to test the various tills for glacial dispersions of gold mineralization from possible subcropping deposits (Averill 1984; Averill and Zimmerman 1986; Gray 1983, 1984). As the overburden drillholes are generally continued a metre or so into bedrock, a geological database is created which can be used to re-evaluate the geophysical interpretation. Diamond drilling of priority targets is then carried out.

In areas of deep overburden cover where targets of low conductivity contrast are sought, selective induced polarization surveying is frequently used before, during, or after the initial drilling phase.

The evolution of the current exploration philosophy in the Casa Berardi region is described with the aid of primarily geophysical case histories of the Golden Pond and Estrades Deposits which differ in

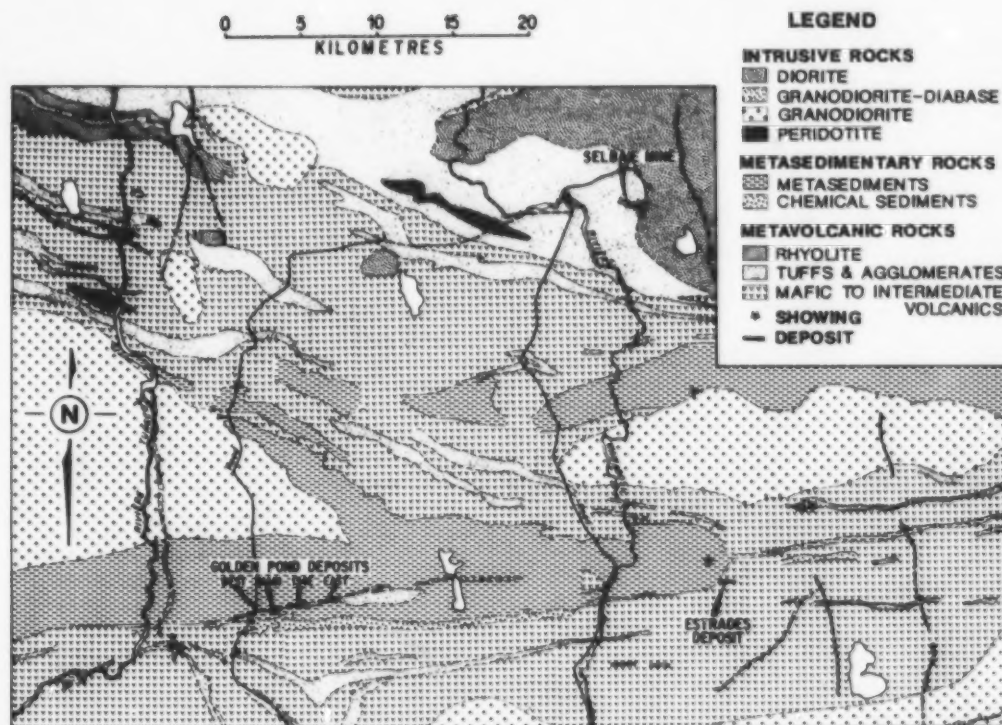


Figure 74.2. Geological compilation of the north-central Abitibi (adapted from MPH Consulting Limited 1987).

their geological settings, mineralogy, and physical characteristics.

In addition, evidence will be presented for the presence of a regional structural feature, known as the Casa Berardi Fault, on both properties.

The emphasis of this paper is toward the prevailing geophysical exploration techniques and the general chronological development in refining these procedures in the Casa Berardi region. The geological descriptions of the Golden Pond and Estrades Deposits, for reasons of space, are brief and general, being biased towards correlating geological events with distinct geophysical signatures and reverse-circulation drilling results.

A detailed geological description of the Golden Pond Deposits is to be found in Pattison *et al.* (1986). Werniuk (1986) and Phillips (1987) present brief but more complete details on the Estrades Deposit. The producing Detour, Selbaie, and Agnico-Eagles Mines are described in Marmont (1986), Deptuck *et al.* (1982) and Wyman *et al.* (1986), respectively.

## GOLDEN POND DEPOSITS

### GENERAL GEOLOGY

Since the initial discovery in 1981 of the Golden Pond Main Deposit in Casa Berardi Township, three other deposits, the West, 134E and East Zones, have been identified. All the deposits are situated in a one to two kilometre wide complex assemblage of clastic and chemical sediments and volcanics — the Golden Pond Sequence — which is bounded to the north and south by banded chert-magnetite iron formation. Younger sediments, typically well bedded feldspathic sandstone, siltstone and mudstone occur north of the Golden Pond Sequence whereas volcanics are inferred to predominate to the south. Well bedded chert-pyrite, oxide-silicate, and graphite-sulphide facies iron formations occur as discontinuous lenses up to 1.5 km in length within the sediments of the Golden Pond Sequence (Figure 74.3).

All the ore bodies are quartz vein type gold deposits, spatially as well as possibly genetically associated with an east-trending regional feature described by Inco Limited as the Casa Berardi Fault. The Casa



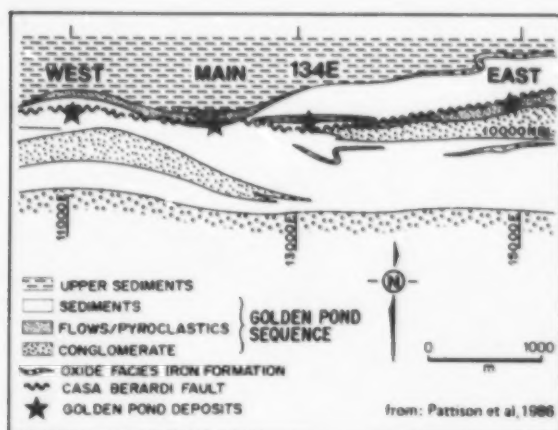


Figure 74.3. Geology of the area around the Golden Pond Deposits (from Pattison et al. 1986).

Berardi Fault is a relatively thin, one to three metre wide, ductile—brittle fault structure usually contained within a unit of graphite- and pyrite-bearing argillite. The fault is not confined to a single stratigraphic horizon and in several places fades out into zones, several tens of metres wide, of complex faulting in broken and deformed rock where the host graphitic sedimentary unit has pinched out. The Casa Berardi Fault continues along strike in another ductile, graphitic sedimentary unit which may be either at the same or at a different stratigraphic level (Pattison et al. 1986).

The magnitude and sense of displacement along the Casa Berardi Fault is not clear. All known potentially economic gold zones on the Golden Pond Property, however, are within a zone of relatively weak ductile deformation which is adjacent to the fault and can be several hundred metres wide. The term Casa Berardi Deformation Zone is being used increasingly to describe this region (Pattison, personal communication, 1988).

## MINERALIZATION

Gold mineralization is associated with pyrite-arsenopyrite-quartz-ankerite veins which vary from single veins less than 1 cm thick to stockworks of multiple, small- to medium-sized veins to large veins over 10 m thick. Although, on a regional scale, the gold mineralization is concordant with stratigraphy, individual vein systems cut lithologic units. A total of approximately 11 680 000 short tons of ore grading 0.22 ounce gold per short ton has been outlined and the East Zone is currently being placed into production (The Northern Miner 1988b).

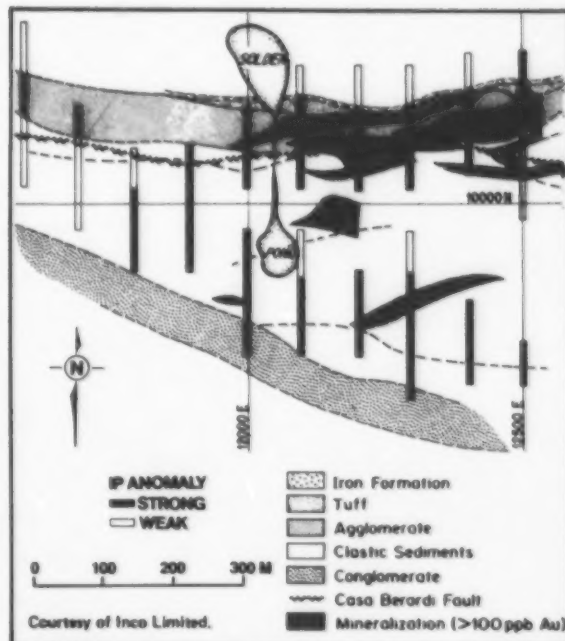


Figure 74.4. Geology of the Golden Pond Main deposit. Induced polarization interpretation superimposed (from Dowsett et al. 1984).

## EXPLORATION

Initially searching for base metals, Inco Limited was attracted to the Golden Pond area by a regional conductive trend on the north flank of a strongly magnetic linear feature which reflects banded iron formation.

Total field magnetic and electromagnetic surveys were carried out at 100 m line and 25 m station intervals over a large area to investigate this airborne trend (Plate 74.1, see Colour Folio near back of book). The geophysical results of these surveys indicated two subparallel conductors in a magnetically quiescent background. Both conductors are of moderate conductance and easily traced using a coil separation of 150 m and transmitting frequencies of 888 and 1777 Hz.

In early 1981, the discovery hole, hole 40670 on line 120+00E, was drilled into the south conductor and intersected 12.6 grams gold per tonne over 6.7 m under 56 m of overburden. The gold is associated with graphite and mudstones which closely trace a conglomerate-turbidite contact along part of its length. Holes drilled beneath and on either side of the discovery hole failed to find any continuation of the mineralization (Dowsett and Krause 1984).

Later testing of the north conductor led to the discovery of the Main Deposit (Figure 74.4). The gold mineralization is generally associated with five to ten percent combined pyrite and arsenopyrite in

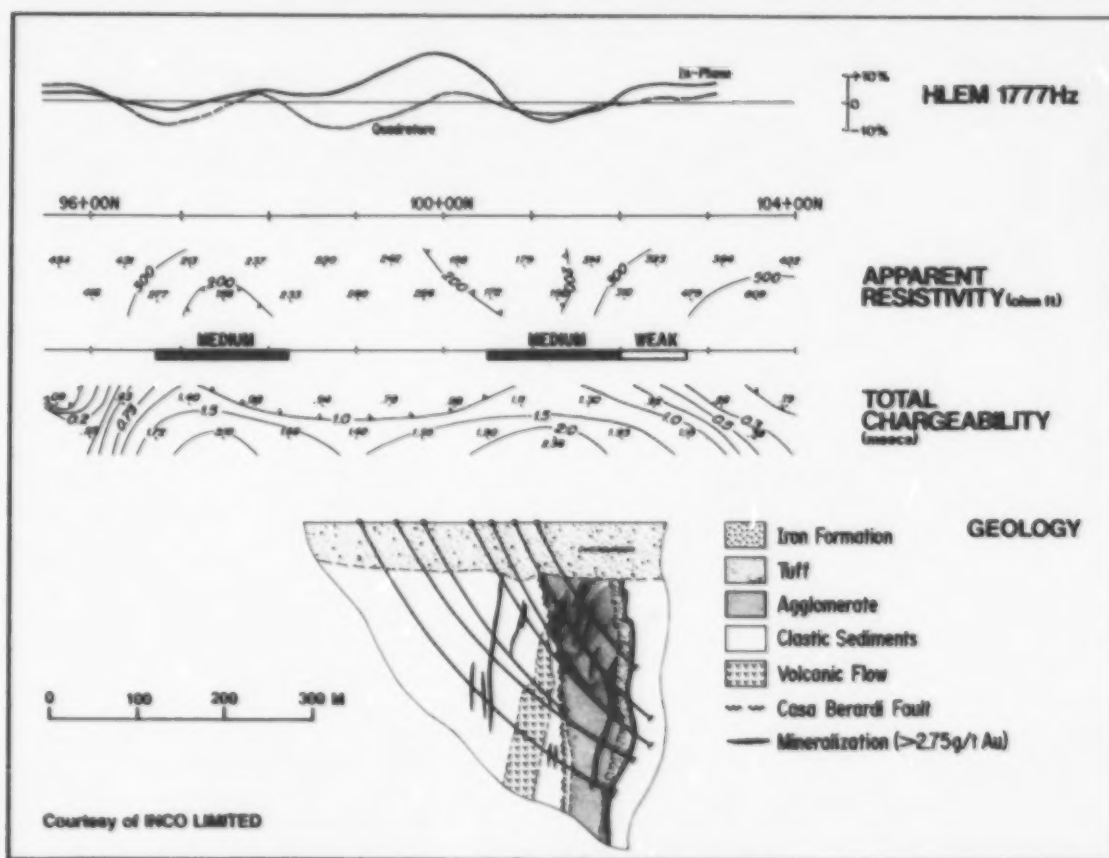


Figure 74.5. Golden Pond main deposit. Geology and geophysical compilation of line 124+00E (adapted from Dowsett *et al.*, 1984).

quartz veins within agglomerates and fine-grained clastic sediments. Bedded graphite–argillite–pyrite chemical sediments were found to be the main causal source of the electromagnetic response (Figure 74.5). The Casa Berardi Fault is generally found within or on the edge of a unit of this type. The Casa Berardi Fault has been traced by drilling over six kilometres of strike length and is the only fault structure followed with any continuity on the Golden Pond Property.

Induced polarization surveying primarily traced the graphitic horizons within the Golden Pond Sequence (Figure 74.4) with a coincident low-resistivity response being recorded over the Casa Berardi Fault (Figure 74.5). A 2.5 kW transmitter and Hunttec Mk III receiver were used with a pole–dipole array. Survey parameters were characterized by a dipole spacing of 75 m and the first two dipole separations only were read (Dowsett and Krause 1984).

Inco Limited carried out heavy minerals geochemical surveys with the reverse-circulation drilling method as part of their in-house research on how best to delineate any further gold deposits in the

area. A major gold–arsenic dispersion train in locally derived Lower Till was successfully traced as far as 400 m downice from the Main Zone (Sauerbrei *et al.* 1987).

These two techniques, the reverse-circulation drilling and induced polarization, were subsequently used to screen conductive horizons and successfully led to the discovery of the East (Sauerbrei *et al.* 1987) and West Zones.

## ESTRADES DEPOSIT

### GENERAL GEOLOGY

The second major discovery in the area, the Estrades Deposit, is located on the Golden Hope Property about 20 km east of the Golden Pond Deposits (Figure 74.2).

The deposit is approximately 1600 m long and has been subdivided into the Main, Central and East Zones (Figure 74.6). An apparently postdepositional fault with a north–northwest to north–south trend separates the Main and Central Zones where a

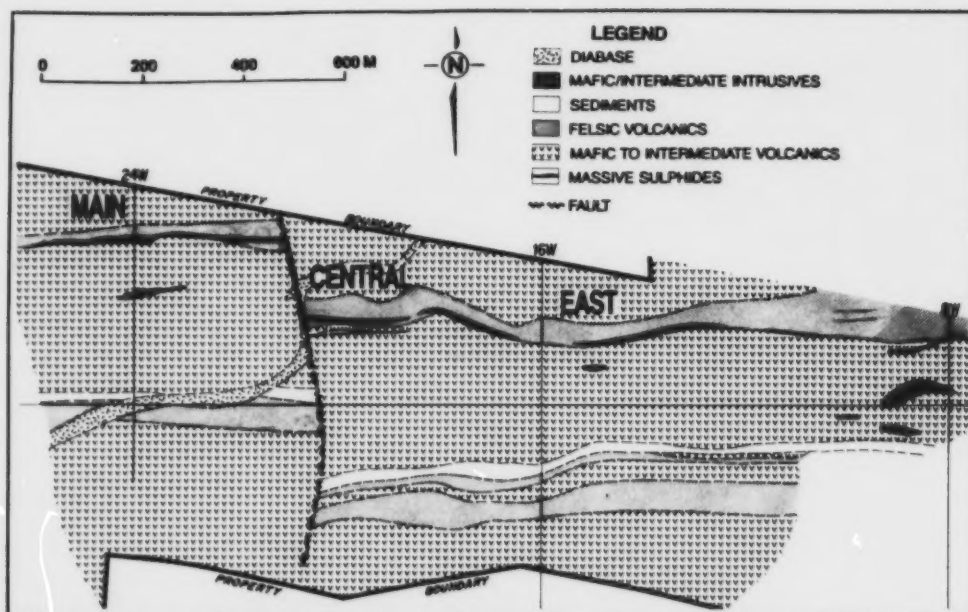


Figure 74.6. Estrades Deposit: 100 m level geology plan.

right-lateral displacement of the deposit of approximately 160 m is noted at the bedrock surface.

The Estrades Deposit consists of a series of subcropping precious metal-bearing massive sulphide lenses located at or near the top of a thin felsic pyroclastic unit (Figure 74.6). The felsic unit is known as the Estrades horizon and is part of an east-striking series of volcanics in which mafic to intermediate flow rocks are dominant. Sedimentary units are rare within the package and consist of argillites, siltstones and greywackes. The higher-grade sulphides are predominantly sphalerite with pyrite and chalcopyrite while the lower-grade zones contain pyrite with sphalerite and chalcopyrite. The massive sulphide segment of the deposit displays a variable width to a maximum of 5 m. Pinching and swelling occurs downdip as well as along strike.

As a rule, disseminated sulphides have not been found in the hanging wall but do occur, over distances of up to 30 m, in the footwall rocks. The greatest widths of disseminated sulphides are associated with the East Zone where pyrite, rather than sphalerite, is the dominant sulphide. The sharp and conformable boundary relation of the ore to the hanging wall and the regular stratigraphic setting of the Estrades Deposit are typical of an exhalative massive sulphide deposit.

The rocks stratigraphically under the massive sulphides have a high degree of sericite alteration and minor chlorite alteration and may have been the locus of postdepositional shearing.

An east-northeast-trending diabase dike is the latest geological feature and has been emplaced along zones of weakness including, in part, the fault crosscutting the deposit.

The deposit subcrops under 12 to 40 m of glacial overburden and has an 80° to 85° dip to the south. A shallower dip of about 60° south in the Central Zone above the 100 m level may be the result of dragging of the mineralized horizon along the crosscutting faults.

#### MINERALIZATION

The Main Zone contains the richest precious and base metal values. The Central Zone of the deposit contains relatively lower grades of base and, to a lesser extent, precious metals.

As of June 1988, the geological mineral inventory of all lenses has been calculated as 2.9 million tons grading 0.11 ounce gold per ton, 9.16 percent Zn, 3.73 ounces silver per ton, and 0.93 percent Cu (The Northern Miner 1988a).

#### EXPLORATION

On a regional scale, as determined from airborne results, the Estrades Deposit is defined by an Input survey as a cluster of three, two- to three-channel electromagnetic responses. These weak responses did not constitute priority targets as more continuous conductive horizons tended to be investigated first in keeping with the geophysical scenario defined at Golden Pond.

During the summer of 1985, as part of a major regional program, the Golden Hope Property was

covered by reconnaissance ground total field magnetic and horizontal loop electromagnetic surveys at 200 m line and 25 m station intervals. Reverse-circulation drilling was then carried out downice from all conductors to delineate any mineralized dispersal trains, and each conductive horizon was tested at least once by diamond drilling.

The Estrades Deposit is nonmagnetic and weakly conductive. It was clearly defined by horizontal loop electromagnetics only at the highest transmitting frequency on lines 24+00W and 16+00W. These responses reflect the more massive sulphide portions of the Main and East Zones, respectively. A coil separation of 150 m and transmitting frequencies of 444 Hz and 1777 Hz were employed. The magnetic results clearly defined the trace of the crosscutting diabase dike but otherwise did not contribute to determining the extent of the deposit (Plate 74.2). It is of interest to note that the reverse-circulation drilling program failed to locate a mineralized dispersion fan downice from the Estrades Deposit due to the presence of an intervening ridge of more competent volcanic material immediately to the south where the overburden is only 10 m thick (Figure 74.7).

In keeping with the regional exploration strategy applied by Teck Explorations Limited, the conductive response on line 24+00W was tested by diamond drilling in late 1985. Hole H-9 returned one of the richest intersections in Canadian mining history: 0.36 ounce gold per ton, 11.65 ounces silver per ton, 2.33 percent Cu, and 28.07 percent Zn over 34.5 feet (The Northern Miner Magazine 1986).

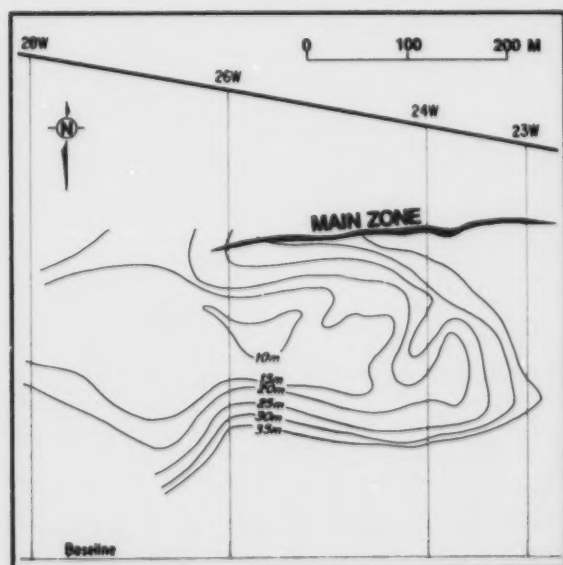


Figure 74.7. Bedrock topography map over the Main Zone of the Estrades Deposit.

Detailed magnetic, horizontal loop, induced polarization, and time-domain electromagnetic test surveys were subsequently carried out in 1986 to determine the full geophysical signature of the Estrades Deposit with a view to tracing the host Estrades horizon and detecting similar mineralization along strike.

A detailed total field magnetometer survey was completed at 25 m line separations over the Main Zone but failed to delineate a distinctive signature for either the deposit or the Estrades horizon.

Horizontal loop electromagnetic surveys were carried out using a cable separation of 150 m and transmitting frequencies of 222 to 7111 Hz. The deposit horizon is virtually untraceable at the three lower frequencies. The 1777 Hz results weakly define the deposit horizon, knowing where this is from drilling, but would probably not be traced with any confidence otherwise and would not constitute a drill target in the general exploration philosophy current in this or most other areas (Figure 74.8). The 7111 Hz data present a much more distinct line-to-line trace of the Estrades Deposit which would more readily be considered a drill target (Figure 74.8).

The stacked HLEM profiles of all transmitting frequencies on line 24+00W illustrate increasing phase rotation with transmitting frequency leading to an inversion of the quadrature response at 7111 Hz (Figure 74.9). This phenomenon is common in the Casa Berardi area where bedrock conductors are steeply dipping and subcrop under conductive overburden. The possible subsequent adverse consequences to an exploration diamond drilling program are most readily illustrated with the aid of a phasor diagram computed using the assumption that the bedrock conductor is in free-air. The solid arrow traces the frequency migration expected for a thin, dipping sheet in free-air as extrapolated from the 222 Hz data (Figure 74.10). The actual field results, shown by the dashed line, while appearing to trace a similar path, deviate significantly from this model between the lowest and middle frequencies causing the conductor to appear weaker and shallower than it actually is with increasing frequency. Interpretation should, therefore, be made at the lowest frequency at which a response is discernable. Theoretically, extrapolation of the curve to very low frequencies would give the most accurate parameters.

Bearing in mind the known variations in bedrock topography in the area, the responses on line 24+00W and those on lines 22+00W could be partially reflecting an overburden-filled valley. Plots of the in-phase (IP) and out-of-phase (OP) anomaly amplitudes over the frequency range show that the in-phase data vary from the half-plane response only at the highest frequencies. The IP/OP ratio curve, however, deviates from the half-plane model, reversing in sign at low frequencies (Figure 74.11). This fact and the significant increase in the apparent conductance at low frequencies, as derived from the



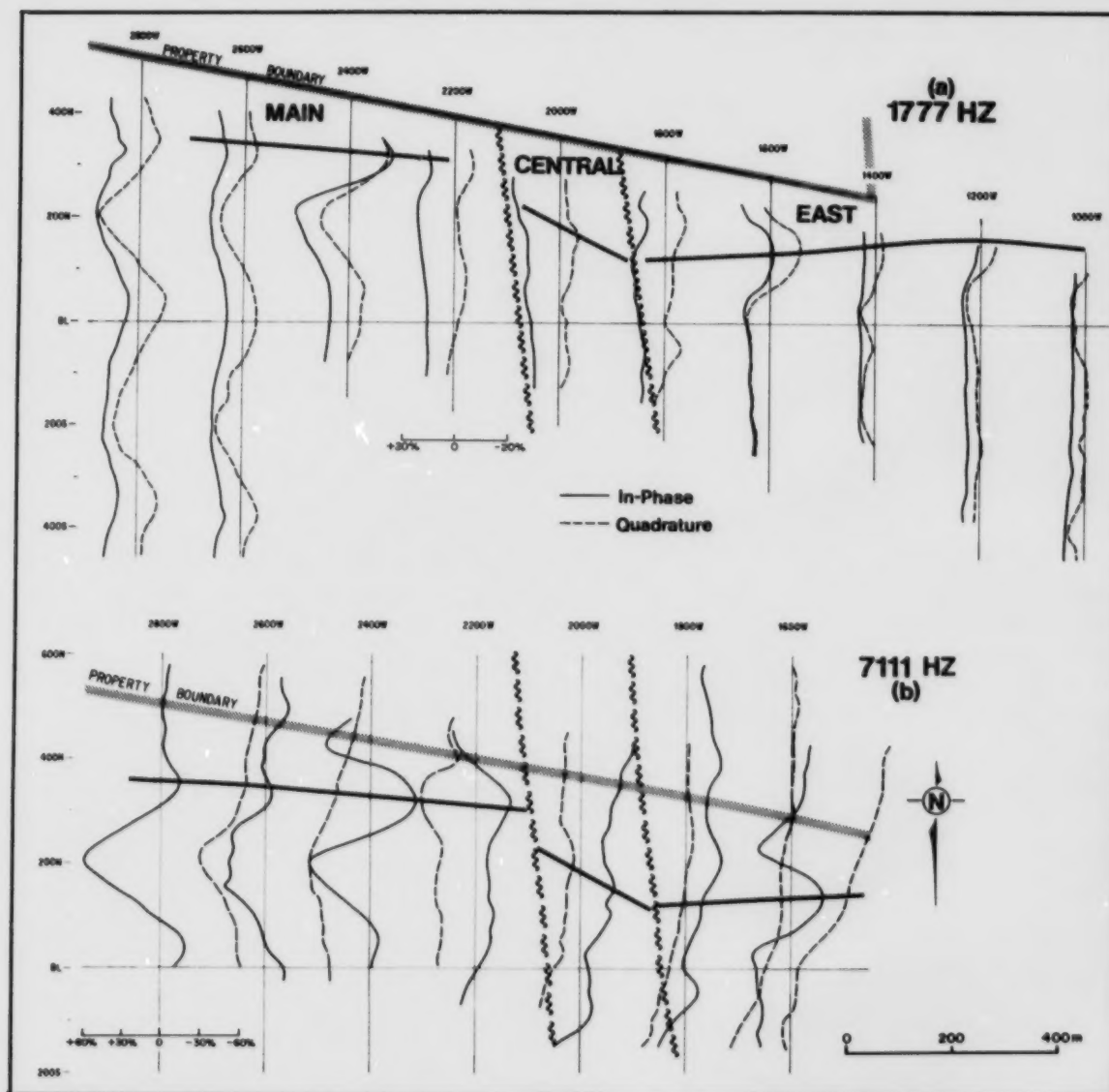


Figure 74.8. Horizontal loop electromagnetic profiles, 1777 Hz, and 7111 Hz, from the Estrades Deposit (using a 150 m coil separation).

phasor diagrams, confirm the presence of a bedrock conductor (Figure 74.11).

A time-domain electromagnetic survey was completed over the Main Zone with survey parameters as shown in Figure 74.12. A base transmitting frequency of 30 Hz was employed and both the horizontal X and vertical Z components were recorded. The results from line 24+00W indicate a poorly conductive narrow source at 3+10N coincident with the Main Zone (Figure 74.13).

The deposit response is first clearly recorded on channel four as a moderate amplitude response

which rapidly decays to very low amplitudes and is last seen on channel thirteen. The Main Zone is therefore characterized by a very short time constant and low conductance which is not unexpected given that the massive sulphides form only a small lens and locally contain up to 50 percent sphalerite by volume.

On adjacent lines to the east and west over the remainder of the deposit, as exemplified by line 21+00W (Figure 74.13), the responses are very much more diffuse and, without *a priori* knowledge, would not by themselves constitute *bona fide* explo-

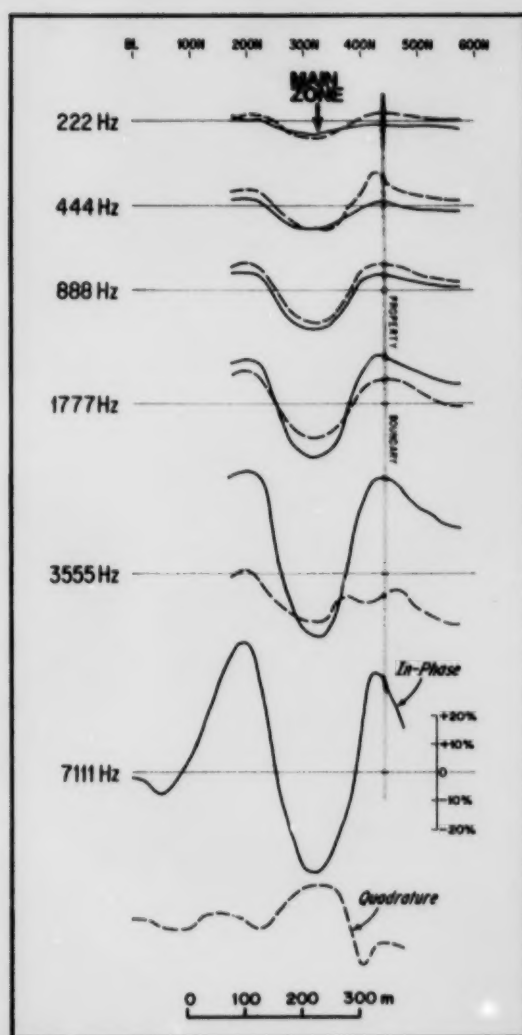
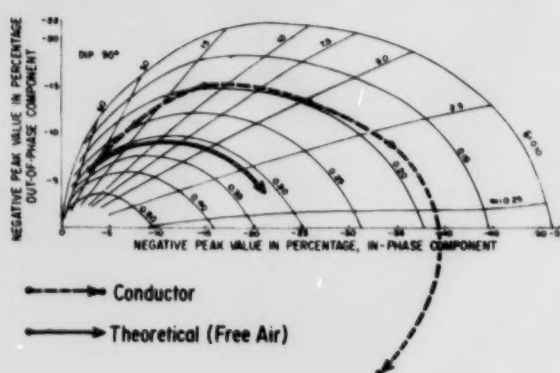


Figure 74.9. Compiled horizontal loop electromagnetic profiles from line 24+00W over the Main Zone of the Estrades Deposit (using a 150 m coil separation).

ration targets. The exception is the response of the East Zone on line 16+00W (Figure 74.13) where a sharp response of short time constant similar to that of the Main Zone on line 24+00W was recorded. The response amplitudes for the East Zone on line 16+00W are very much lower than those measured over the Main Zone.

Induced polarization surveys were completed using a 7.5 kW Hunttec transmitter and Mk IV receiver. A pole-dipole array with a dipole spacing of 50 m and dipole separations of 1 to 4 was found to be the most successful approach in terms of target identification and resolution. It was found to be im-

## FREQUENCY MIGRATION 222Hz to 7111Hz



Phasor diagram for conducting half-planes dipping at 90 degrees (after Nair et al, 1968)

Figure 74.10. The effect of conductive overburden on the horizontal loop electromagnetic responses on line 24+00W over the Estrades Main Zone.

possible to obtain reliable data using a dipole-dipole array due to a combination of geological, atmospheric and cultural noise evident at the time.

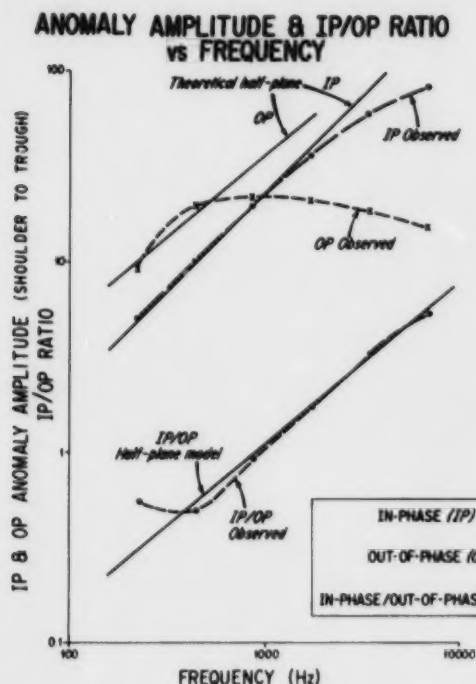
The induced polarization results are compared with the horizontal loop data on line 24+00W over the Main Zone (Figure 74.14). The deposit is moderately polarizable but has no distinct low-resistivity response, a fact not altogether unexpected given the depth and conductivity of the overburden and the high percentage of sphalerite which reduced the conductance of the sulphide mineralization as a whole.

A plan map of the first separation total chargeability data clearly defines both the deposit and the continuation, both east and west, of the host Estrades horizon (Figure 74.15). The greatest volume of disseminated sulphides is found in the foot-wall of the East Zone and gives rise to the broadest chargeability responses. Combined with the much lower volume percentage of sphalerite and increased pyrite content, this results in the highest amplitude responses being recorded over the Estrades Deposit.

## EXPLORATION PHILOSOPHY

We can thus conclude that, while the geological setting and airborne geophysical signatures of the Golden Pond and Estrades Deposits are in complete contrast, the ground geophysical results indicate distinct similarities: a) both are nonmagnetic; b) horizontal loop electromagnetic surveys define in whole or in part the mineralized horizons, especially at the higher frequencies; c) both are associated with moderately polarizable horizons which extend laterally beyond the economic mineralization.

The magnetic results were instrumental in delineating lithologic units such as iron formation and



IP/OP RATIO & CONDUCTANCE (d) vs FREQUENCY

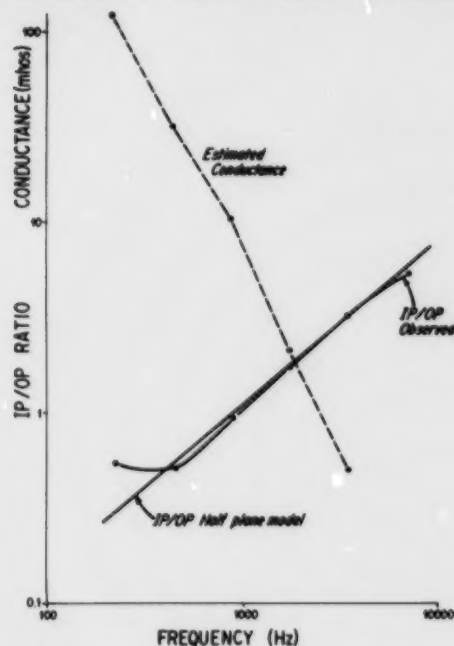


Figure 74.11. Horizontal loop electromagnetic interpretation compared with theoretical half-plane models. Line 24+00W, Estrades Main Zone.

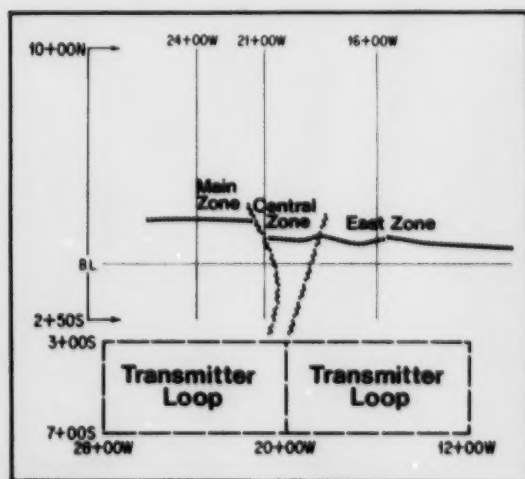


Figure 74.12. Estrades Deposit: Time-domain electromagnetic (Geonics EM-37) survey parameters.

diabase dikes and structural features which enabled a more complete geological interpretation to be made. Magnetometer and horizontal loop electromagnetic surveys should therefore be completed over the entire property for initial selection of target

horizons. These horizons can then be further evaluated using a combination of induced polarization and reverse-circulation drilling surveys. Reverse-circulation drilling will not necessarily directly lead to the discovery of blind deposits such as the Estrades Deposits but will contribute significantly to the geological database and consequently the target selection process.

## GOLDEN HOPE PROPERTY: BOULDER MOUNTAIN TREND

### AREA SELECTION

Having defined the necessary prerequisites for targeting areas potentially containing economic mineralization similar to that previously described, attention was turned to the remainder of the Golden Hope Property.

The airborne geophysical results over the northern sector of the property indicate a regional conductive horizon which is believed to be along strike from the airborne expression of the Casa Berardi Fault as mapped at Golden Pond. The conductive horizon is not continuous between the Golden Pond and Golden Hope Property. The conductor, however, lies within a quiescent magnetic background—interpreted to reflect sediments—several hundred metres to the north of an extensive, east-trending iron formation. The iron formation is highly mag-

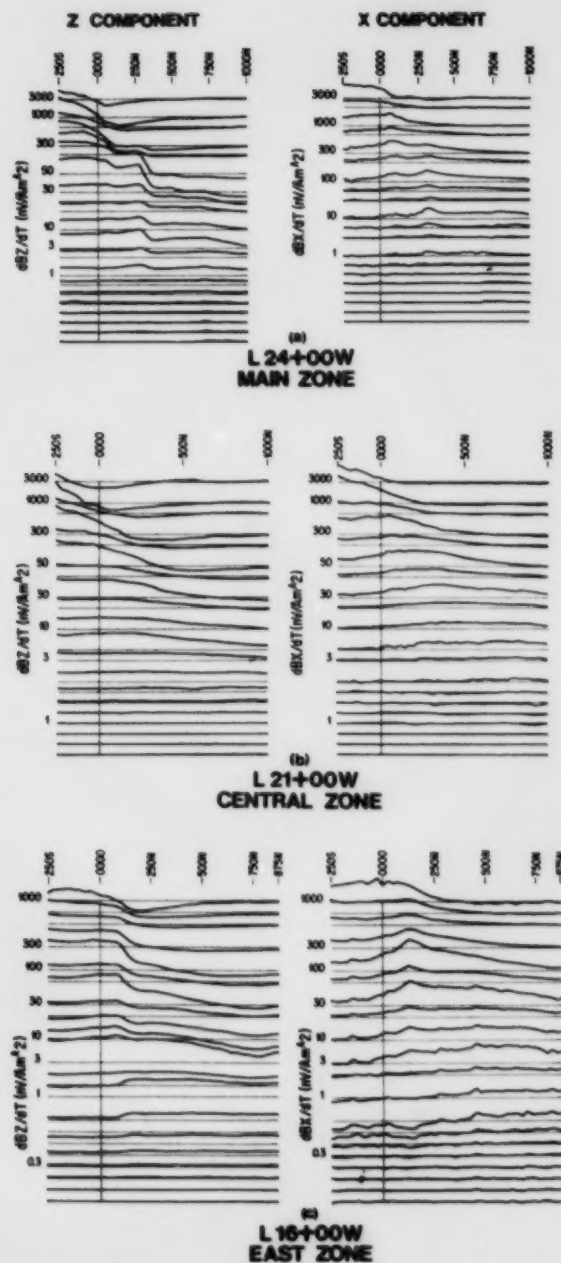


Figure 74.13. Estrades Deposit: EM-37 results from the Main, Central, and East Zones.

netic and nonconductive. This geophysical scenario is identical to that at Golden Pond and the region within 300 m of the conductive horizon, therefore, defines a natural target area for similar gold mineralization.

## EXPLORATION

Subsequently, an exploration program was carried out using survey parameters similar to those successfully employed at both Golden Pond and over the Estrades Deposit. This approach successfully delineated an east-trending graphitic fault/shear zone coincident with the airborne response. Situated in a suite of sedimentary units known as the Boulder Mountain Trend, this fault zone is characterized by intense shearing localized in thin graphitic units and by minor brittle deformation.

Ground geophysical exploration along the Boulder Mountain Trend was not as straightforward as in the case of the Golden Pond and Estrades Deposits. The overburden cover in this sector is among some of the deepest encountered in the region, ranging from 40 to over 100 m in depth. As the overburden is also very conductive, the electrical surveys were not always able to adequately delineate bedrock features with the survey parameters defined previously.

The horizontal loop survey, using a coil separation of 150 m, outlined a discontinuous yet distinctive conductive horizon at the transmitting frequency of 1777 Hz (Plate 74.3).

The ground magnetic data confirmed the airborne results and, similar to the results at Golden Pond, did not reveal a magnetic response associated with the east-trending fault/shear zone as traced by the electromagnetic survey.

The induced polarization method was the most successful in delineating the graphitic fault/shear zone as well as defining the more polarizable sections, as illustrated by the Fraser filtered presentation of the total chargeability results (Figure 74.16). In order to retain spatial resolution and improve depth of exploration, it was necessary to extend dipole separations up to  $n = 6$  while using a dipole spacing of 50 m.

Low-resistivity responses are noted semicoincident with the higher amplitude chargeability anomalies and horizontal loop data. This indicates that the responses must be due to a bedrock feature such as highly conductive massive sulphides or graphite given the depth and conductivity of the overburden. This geophysical signature is identical, as far as can be determined from the results on both properties, to that recorded over the Casa Berardi Fault at Golden Pond.

## GEOLOGY AND MINERALIZATION

A simplified geological section from line 22+00E is shown with corresponding horizontal loop and induced polarization results (Figure 74.17). The diamond drilling indicates that the low-resistivity and broad chargeability responses lie wholly within metasediments and are located at, and to the south of, a contact with mafic volcanics to the north. A number of narrow graphitic shear zones were intersected within the sediments and up to 50 m south of



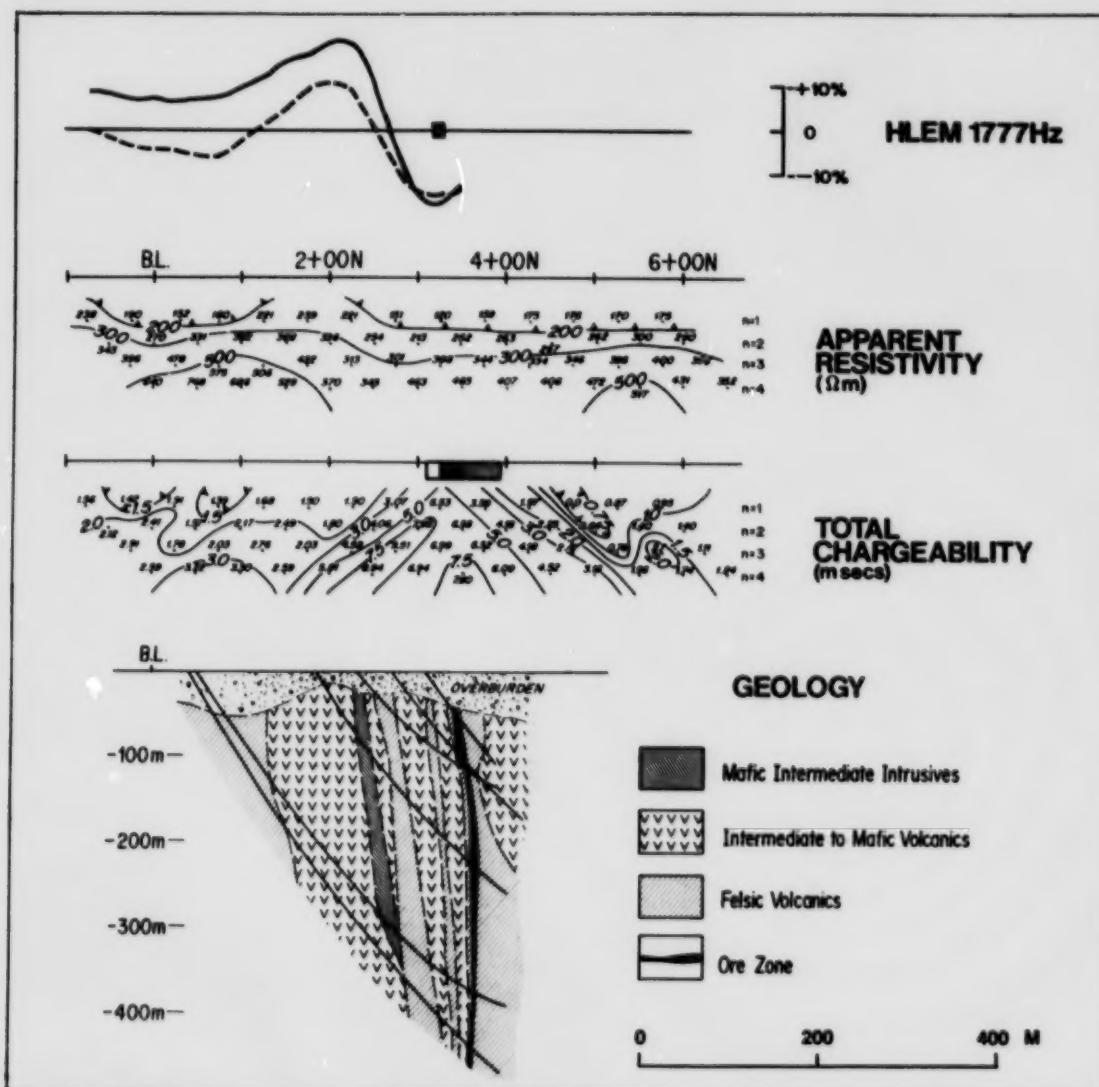


Figure 74.14. Estrades Deposit Main Zone. Geology and geophysical compilation of line 24+00W.

the sedimentary/volcanic contact. One hundred metres south of the contact, and at the southern edge of the interpreted chargeability anomaly, a major graphitic argillite shear zone was delineated and is believed, from the geological and geophysical evidence, to be the eastward extension of the Casa Berardi Fault from the Golden Pond Property.

Exploration to date has revealed that the main graphitic horizon appears to be transgressive on both the Inco-Golden Knight and the Golden Hope Properties. This suggests that the graphite may not be sedimentary but may have been produced under hydrothermal conditions such as may be associated with the formation of a major regional fault.

The graphitic zones on the Golden Hope Property, taken as a whole, correlate well with the induced polarization response on line 22+00E. The lack of any electromagnetic response is most probably due to the depth and conductivity of the overburden cover being too great for the target to be resolved with this method. As indicated on the section, anomalous gold values have been intersected associated with quartz-carbonate veining in sediments up to 200 m south, and along the extent, of the main graphitic fault/shear zone. These results complement the Golden Pond geological scenario where gold mineralization is found in sediments within 300 m of a major regional fault.

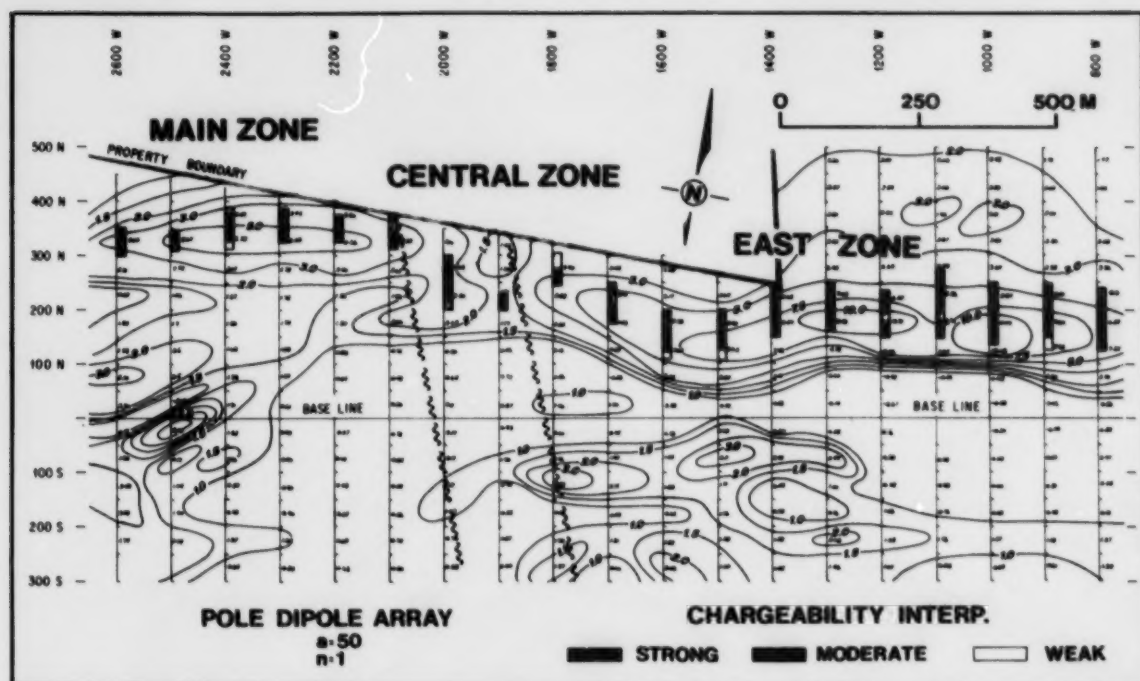


Figure 74.15. Total chargeability plan map, dipole separation  $n = 1$ , Estrades Deposit.

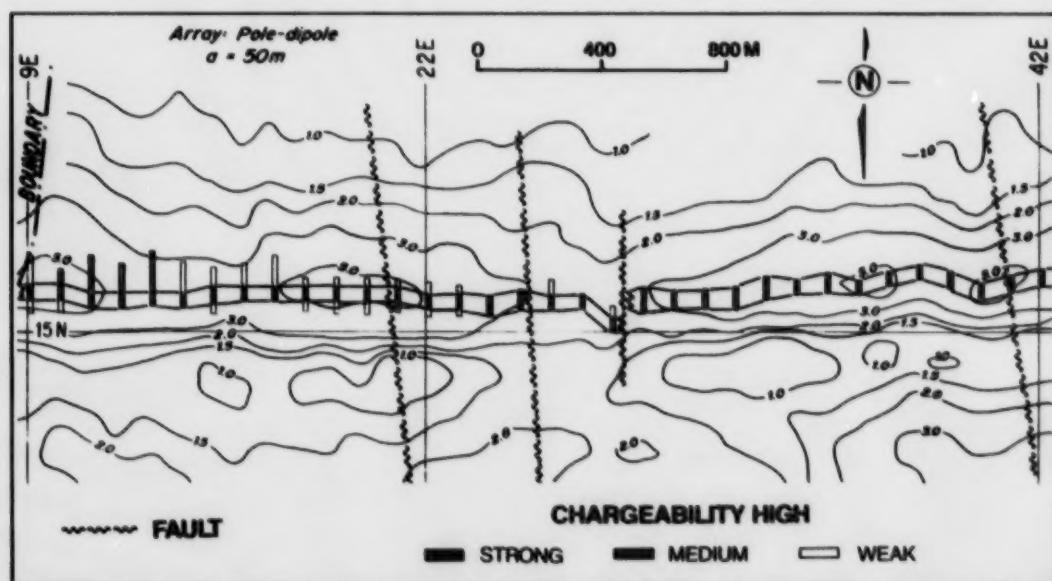


Figure 74.16. Fraser filtered total chargeability plan map over the Boulder Mountain Trend on the Golden Hope Property. Induced polarization interpretation is superimposed.

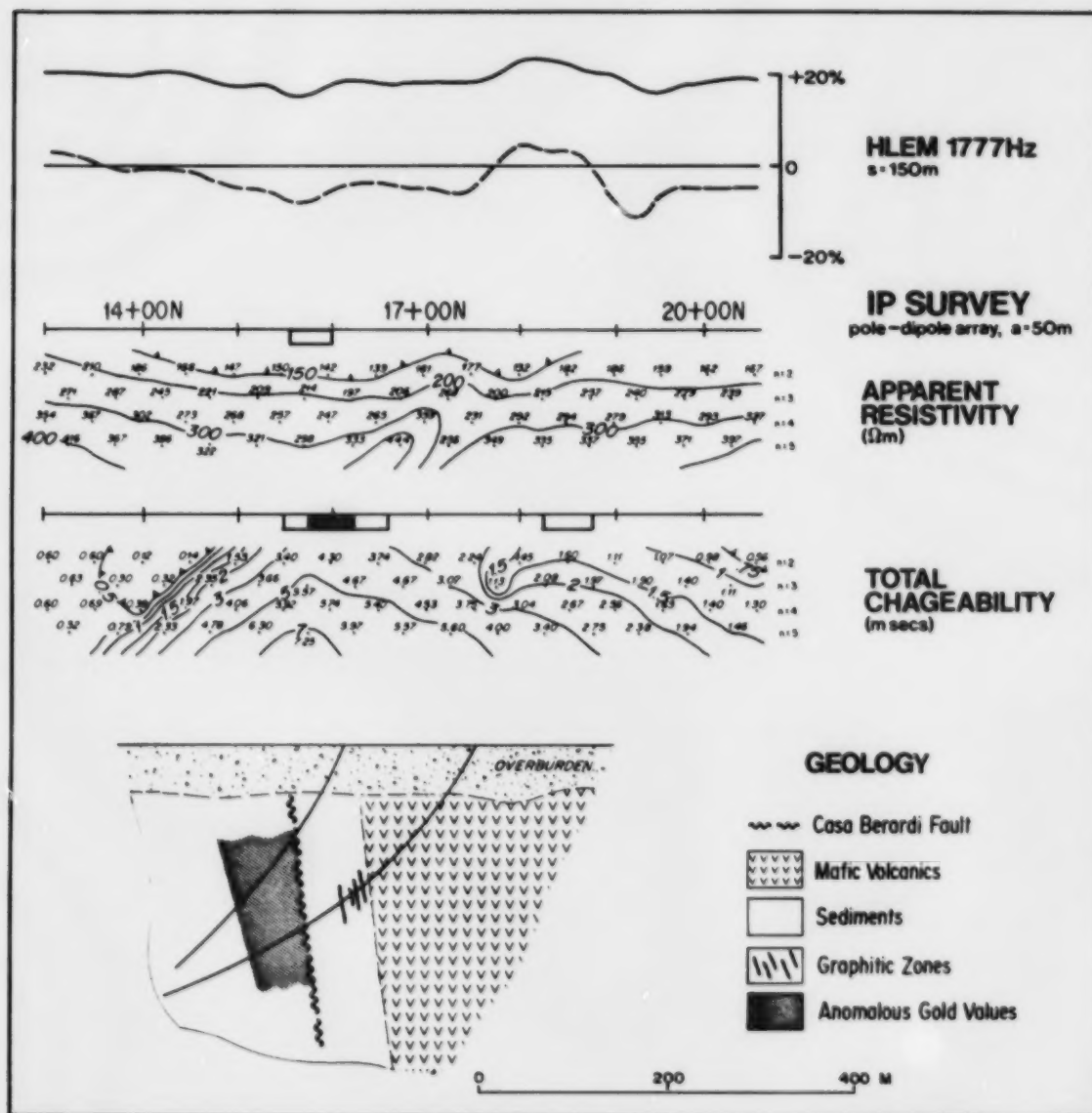


**Figure 74.17. Boulder Mountain Trend, Golden Hope Property. Geology and geophysical compilation of line 22+00E.**

**GOLDEN HOPE PROPERTY: CASA BERARDI DEFORMATION ZONE**

A generalized geology map of the Golden Hope Property, derived from the geophysics and extensive drilling results, is presented with the locations of major shear zones and faults (Figure 74.18). If the main fault/shear zone within the Boulder Mountain Trend is indeed the Casa Berardi Fault, then one might reasonably expect it to be situated in a suite of rocks constituting the Casa Berardi Deformation Zone at this location. The Casa Berardi Fault is situ-

ated near the northern extent of the sedimentary units.

The actual width of the Casa Berardi Deformation Zone in the Golden Hope area is not easy to determine with any certainty. It is apparent that there are a number of east-trending fault/shear zones extending across the property in both the sediments and volcanic units to the south of the Casa Berardi Fault, including a major shear zone to the south of the Estrades Deposit. If the Casa Berardi Deformation Zone is confined to the sedimentary units then it would be approximately 1 km wide.

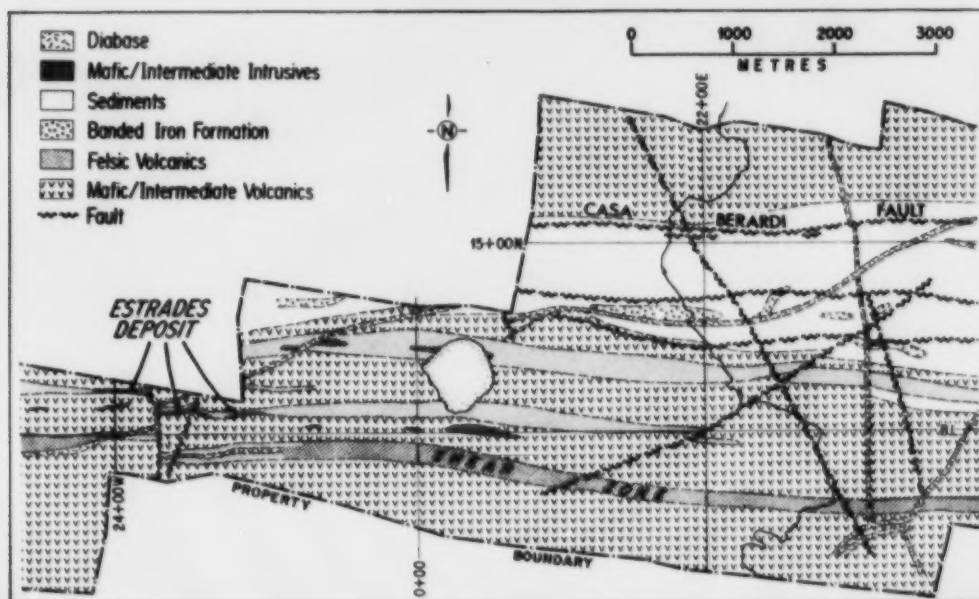


Figure 74.18. Generalized geology and structural interpretation of the Golden Hope Property.

The scale of east-west deformation on the property, however, suggests that the deformation zone may be 2 km or more in width and encompasses both the Estrades horizon and the Boulder Mountain Trend. Obviously far more information needs to be gathered from the area between the Golden Pond and Estrades Deposits for any hypothesis to be confirmed or disproved.

It remains to be stated that the width, intensity of deformation, and currently inferred strike length of the Casa Berardi Deformation Zone are not as extensive as those associated with the Destor—Porcupine and Larder Lake—Cadillac Breaks. Nevertheless, significant economic mineralization has been found within, and possibly adjacent to, the Casa Berardi Deformation Zone to date, as defined in this paper. Continued exploration along the lines described above should lead to the discovery of more deposits in the years to come.

## ACKNOWLEDGMENTS

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# 75. L'Application des Méthodes Géophysiques et Géochimiques pour la Recherche des Gisements de Sulfures Massifs de Type Perkoa

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## RÉSUMÉ

Le gîte sulfuré volcanogénique de Perkoa (Zn-Pb-Ag-Cd), découvert en 1982 par un projet de recherche minière PNUD/Gouvernement, est constitué d'une lentille subverticale de sulfures massifs de 300 m de long, 1 à 15 m de large, s'étendant jusqu'à 500 m de profondeur et localisée dans une série de tufs acides d'âge birrimien. Il s'agit là de la première découverte de sulfures massifs dans la ceinture de schistes verts birrimienne d'Afrique de l'Ouest. La totalité de cette ceinture est ainsi devenue une cible potentielle pour d'autres découvertes de sulfures massifs. Perkoa fournit un modèle pour de futures campagnes d'exploration dans la région.

Ce gîte a été découvert au cours d'une campagne de prospection géochimique en sol. L'échantillonnage, selon une grille de 400 m sur 400 m, a donné deux anomalies en Zn relativement faibles au-dessus du corps minéralisé. Par la suite, une prospection détaillée à une maille de 25 m sur 25 m a confirmé la présence d'une zone anormale en Zn (>200 ppm) de 550 m sur 250 m. Les seuls affleurements existants sont situés légèrement au sud du corps minéralisé et sont constitués de tufs felsiques silicifiés enrichis en Fe et Mn. Le premier sondage a traversé un horizon riche en sulfures de zinc.

Par la suite, cet horizon a été délimité avec plus de précision grâce à des méthodes géophysiques au sol traditionnelles (magnétisme, électromagnétisme en domaine-temps et en domaine-fréquence, polarisation provoquée et résistivité). Dans cet environnement, toutes ces méthodes donnent de bons résultats. Perkoa est marqué par une signature magnétique nette et bien reconnaissable (200 nT), par une bonne réponse EM à environ 800 Hz et aux fréquences plus basses (la conductivité estimée est de 50 siemens) et par une forte réponse en PP (20 mV/V).

La plupart des anomalies géochimiques en Cu-Zn-Pb découvertes à ce jour, y compris Perkoa, sont liées à des affleurements ou à des minéralisations proches de la surface. Il est à craindre que la prospection géochimique ne permette pas de détecter des minéralisations sous-jacentes dans les zones recouvertes d'une cuirasse latéritique indurée, et/ou dans les zones avec un profil d'altération relative-

ment épais. Du fait que Perkoa donne une réponse magnétique bien reconnaissable et représente un excellent conducteur électrique (comme d'autres sulfures massifs volcanogéniques du même type), la géophysique aéroportée peut offrir les techniques appropriées pour détecter avec précision, et d'une manière rapide et efficace, d'autres gîtes du type Perkoa. Que ceux-ci soient regroupés en essaim dans la région de Perkoa ou ailleurs dans la ceinture de roches vertes birrimienne.

## ABSTRACT

The Perkoa volcanogenic (Zn-Pb-Ag-Cd) sulphide occurrence, discovered in 1982 by a UNDP/Government exploration team, consists of a steeply dipping massive sulphide lens 300 m long, 1 to 15 m wide and 500 m in depth extent located within a sequence of acid tuffs of Birrimian age. This is the first significant massive sulphide body found to date in the Birrimian greenstone belt of West Africa. All of this greenstone belt is now a viable target area for additional massive sulphide discoveries. Perkoa provides us with a model to guide further exploration in the region.

Soil geochemistry can be credited as the primary discovery tool. The initial reconnaissance survey at 400 by 400 m spacing showed two weak Zn anomalies over the body. Subsequent detailed coverage at 25 by 25 m confirmed the existence of an area of 550 by 250 m anomalous in Zn (> 200 ppm). The only outcrop is located just south of the mineralized body and consists of silicified felsic tuffs enriched in Fe and Mn. Initial drilling intersected a target rich in zinc sulphides.

The target was subsequently delineated by traditional ground geophysical techniques including magnetics, time and frequency-domain electromagnetics and induced polarization/resistivity. All methods work well in this environment. Perkoa gives a distinct and recognizable magnetic signature (200 nT), a good EM response at about 800 Hz and lower (the estimated conductance is 50 siemens) and a strong IP response (20 mV/V).

Most of the Cu-Zn-Pb geochemical anomalies discovered to date, including Perkoa, reflect outcropping or near-surface mineralization. There is a growing concern that the geochemical method may not be detecting buried mineralization in areas of

hard lateritic caps and/or where the weathered layer is relatively thick. Since Perkoa gives a recognizable magnetic signature and is a good electrical conductor (like other volcanogenic sulphides of its type), appropriate airborne geophysical techniques may offer the best possibility of pinpointing, in a fast and cost-effective manner, other existing Perkoa-type bodies clustered in or around the Perkoa area or locations elsewhere in the Birrimian belt.

## INTRODUCTION

En 1977-78, l'association Projet des Nations Unies UPV 74/004 - BUMIGEB (ex BUVOGMI), dans le cadre de sa prospection géochimique régionale sur les sols birrimiens du Burkina Faso (ex Haute-Volta) avait permis la découverte de nombreuses anomalies géochimiques et d'indices de minéralisations tant en Cu qu'en Pb, Ni et Zn. La plupart de ces indices furent réétudiés par prospection semi-détaillée en 1980. Certains ont été confirmés et même accentués, dont le plus évident était celui en Zn et Pb à l'ouest de Perkoa. Des travaux de détail furent alors entrepris en 1981 qui amenèrent, en janvier 1982, la découverte du premier amas de sulfures massifs dans le birrimien de l'Afrique de l'Ouest. Le nombre de sondages effectués à ce jour sur le site de Perkoa dépasse 50.

Plusieurs indices de ces sulfures existaient déjà en Côte-d'Ivoire et au Burkina Faso. Citons notamment l'indice de Cu-Ni des pyroxénolites de Semapleu dans la région de Man en Côte-d'Ivoire, et pour le Burkina Faso la région de Gaoua où, de 1929 à 1940, la Compagnie Equatoriale des Mines exploite une lentille de 5000 t de chalcosine présentant des teneurs de 4 à 50 pourcent de Cu. On peut encore citer, toujours au Burkina Faso, les indices de Pb-Cu à Gan, de Cu+Mo à Goren ou le récent indice de Zn-Pb-Au de Koupéla Nagsène. Cependant, Perkoa est actuellement le seul gisement de sulfures de taille respectable de l'Afrique de l'Ouest, d'où son importance de modèle pour les prospections futures. C'est dans cette optique que furent levées les nombreuses mesures géochimiques et géophysiques dont nous allons parler.

## GÉOLOGIE ET TECTONIQUE REGIONALE

Perkoa est situé (Figure 75.1) dans la partie Sud du craton ouest-africain, connue sous le nom de Dorsale de Man. Celle-ci est restée stable depuis la fin de l'orogénèse éburnéenne ( $\pm 1800$  Ma) et renferme des roches d'âge archéen et protérozoïque inférieur. Dans la continuation de cette dorsale au NE, on trouve, après la dépression de Gao (200 km), le massif du Hoggar qui renferme des roches de même âge et de même origine et qui ont subi deux orogénèses plus récentes: l'orogénèse kibirienne (1100 Ma) et l'orogénèse pan-africaine (550 Ma).

La Dorsale de Man peut se diviser en deux zones: une zone de semi-plateforme éburnéenne formée d'Antébirrimien (3000 - 2500 Ma) et une zone de sillons constituée essentiellement de Birrimien. C'est dans cette dernière que se trouve le gisement de Perkoa. Plusieurs de ces sillons apparaissent au Burkina Faso. Ils ont entre 20 et 50 km de large et 100 à 400 km de long suivant une orientation NE (Figure 75.2).

La limite entre les formations birrimiennes et antébirrimiennes est souvent malaisée à établir car on a, dans la zone de contact, des phénomènes de rétro-métamorphisme dus à des intrusions de granites éburnéens qui ont parfois masqué le métamorphisme de degré élevé des roches antébirrimiennes (allant du faciès à amphibolite au faciès à granulite). Le faciès des formations birrimiennes ne dépasse que rarement celui des roches vertes. Ce critère est le seul employé, en l'absence de datation isotopique, pour distinguer ces deux formations.

## FORMATIONS BIRIMIENNES

Elles peuvent être divisées en trois groupes:

1. Un groupe basal de roches métavolcaniques et volcano-sédimentaires renfermant des coulées de lave, des roches pyroclastiques et des roches sédimentaires détritiques déposées dans un milieu marin.

Elles possèdent souvent un degré de métamorphisme modéré provenant de l'orogénèse éburnéenne.

2. Un groupe sédimentaire plus jeune comprenant des grès grossiers, des grauwwacks et des conglomérats de base suivis d'un dépôt flyscholide.
3. Un groupe de roches plutoniques caractérisé par l'intrusion de granodiorites et de tonalites (2170 Ma), la phase maximale de granitisation de l'orogénèse éburnéenne (2100 à 1950 Ma) et l'intrusion de petits laccolites de granites calco-alcalins, de granodiorites et de syénites.

Deux des plus importants sillons de roches vertes qui traversent le Burkina Faso ont été étudiés conjointement par le PNUD et le BUMIGEB depuis plusieurs années. La direction générale de ces sillons est NNE vers le Sud pour changer à NE au centre du Burkina Faso (Figure 75.2). Leur structure est plus compliquée entre Yako, Kongoussi et Kaya (au Nord de Ouagadougou) où on voit apparaître des directions E et SE. Ces deux ceintures de roches vertes ont leur propre particularité. Il convient donc de les étudier séparément.

## LE SILLON DE BOROMO

Il est situé à l'Est du sillon de Houndé. La puissance des formations birrimiennes y est très irrégulière, montrant une paléosurface de la granodiorite recouverte par l'accumulation progressive de matériaux volcaniques et volcano-sédimentaires.

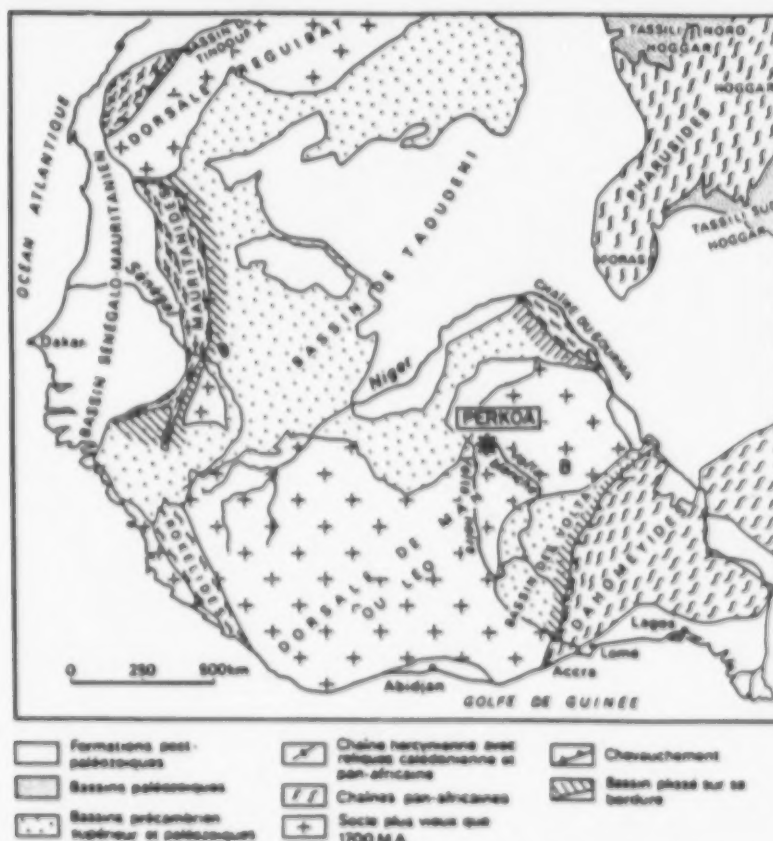


Figure 75.1. Le craton ouest-africain et la chaîne des Dahomeyides (d'après Bessoles et Trompette 1980).

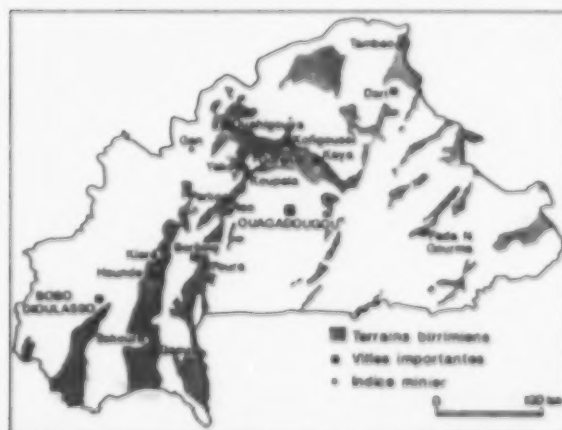


Figure 75.2. Les terrains birimien au Burkina Faso (d'après PNUD 1984, en préparation).

On distingue d'Ouest en Est trois séquences qui peuvent être répétitives: rhyodacitique, andésitique

et basaltique. La plupart des indices de sulfure apparaissent dans ce sillon (Perkoa, Goren, Gaoua, Koupéla, etc.). On y trouve aussi des minéralisations aurifères, et des horizons à Mn et Co mais sans teneurs élevées. Les couches graphitiques sont importantes et nombreuses.

#### LE SILLON DE HOUNDÉ

Cette bande est plus large que la précédente et contient plus de formations métasédimentaires. Les séquences sont andésitiques et dacitiques avec de faibles anomalies en Cu, Zn et Ni. Notons aussi de fortes accumulations de Mn (Kiere, Sokoura), des minéralisations aurifères et quelques couches graphitiques.

Les deux sillons montrent les mêmes phénomènes intrusifs:

1. On trouve des intrusions syn- à tardi-tectoniques dont les effets sont différents en fonction de la profondeur de mise en place et de la nature de la roche affectée. Par ce processus, on peut avoir formation de diorites dans le Birimien (ex.: Goren).



2. On ne trouve pas de pegmatites mais de très nombreux filons de quartz.

Au contact du socle antébirrimien, on note une remobilisation parfois intense. Les différentes minéralisations sont de deux ordres, syngénétique et diagénétique, avec ou sans remobilisation.

## GÉOGRAPHIE ET GÉOLOGIE DE PERKOA

Perkoa se trouve à 150 km à l'Ouest de Ouagadougou et 15 km au NNW de Réo, chef lieu de la province (Figure 75.2). Cette position constitue plusieurs atouts pour le gisement:

- Le réseau électrique existe à Réo.
- On se trouve à 30 km d'une route goudronnée.
- On se trouve aussi à 30 km du chemin de fer Ouagadougou-Abidjan.

Le relief à Perkoa est relativement plat et les seules élévations sont représentées par les restes d'une cuirasse latéritique, dominant d'une dizaine de mètres une région de savane arborifère semi-aride. A l'aplomb du gisement se trouve un petit affleurement de tufs ferrugineux silicifiés (Figure 75.3), présentant des teneurs géochimiques élevées (voir plus loin). A part cette occurrence, il n'existe aucun autre indice géologique de la présence de sulfures massifs à Perkoa et les seuls renseignements que l'on possède proviennent des sondages. Ceux-ci nous indiquent que le gisement se trouve au contact entre une zone de tufs et laves silicifiés et un massif de granodiorite (Figure 75.4).

Le minerai se présente essentiellement sous la forme de pyrrhotine et de blende avec un peu de

pyrite et de galène. On peut distinguer une minéralisation disséminée, contenant ces trois sulfures, et une minéralisation massive, répartie en trois classes:

1. *La minéralisation bréchique.* Elle se trouve au toit géométrique, ce qui semble indiquer que la série est renversée. Elle contient, en plus des trois minéraux cités plus haut, de la magnétite, de la tourmaline, de l'illménite et de la chalcoppyrite. On y trouve entre 5 et 20 pourcent de sulfures.
2. *La minéralisation massive s.s.* Elle renferme 100 pourcent de sulfures composés essentiellement de blende avec un peu de pyrite et pyrrhotine. Signalons aussi la présence de magnétite, de mispickel et de traces de barytine.

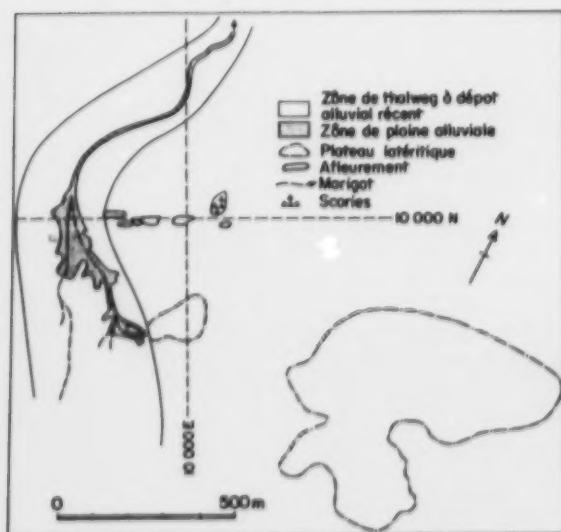


Figure 75.3. Géologie et géomorphologie autour du gisement de Perkoa (d'après Minorex 1983).

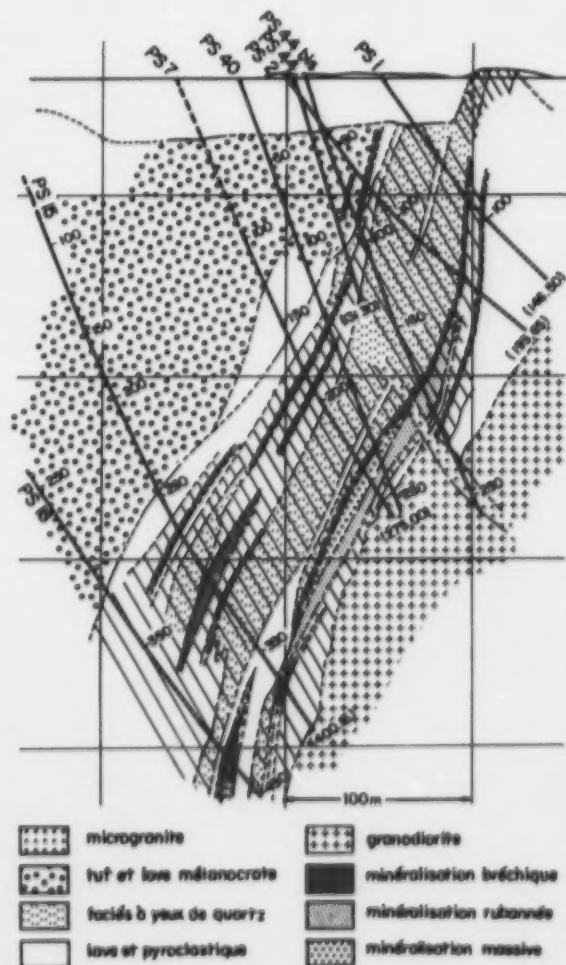


Figure 75.4. Coupe géologique à travers le gisement de Perkoa selon la cote 9975E (d'après Pannaroya 1986).

3. *La minéralisation rubanée.* Elle présente trois faciès: pyrite et un peu de pyrrhotine et blende, barytine et blende, magnétite.

## GÉOCHIMIE

Perkoa fut découvert grâce à une prospection géochimique régionale des sols. La maille d'échantillonnage utilisée était de 400 par 400 m avec prise de l'échantillon à une profondeur de 30 cm. Cela a permis de mettre en valeur deux points anomaux en Zn qui indiquaient respectivement une valeur de 214 et 286 ppm pour un fond régional de 20 à 30 ppm. Comme on peut le voir sur la Figure 75.5, d'autres anomalies supérieures à 100 ppm existent dans la région. Elles ont été, pour la plupart, étudiées par prospection semi-détaillée mais n'ont donné aucun résultat favorable. Perkoa, par contre, montre une très belle anomalie (Figure 75.6) quand on utilise une maille de 50 par 25 m. Les éléments analysés ont été: Cu, Pb, Zn, Ni, Mn, Au, Ag et Co. En plus du Zn, le Pb et l'Ag montrent des anomalies assez fortes sur le gisement.

Toutefois, on remarque en regardant la Figure 75.6 que le Zn donne une auréole de dispersion assez large, à teneur relativement faible, alors que le Pb (Figure 75.7) et l'Ag cernent assez bien la zone avec des teneurs élevées par rapport au fond régional. Ces valeurs du fond régional sont en-dessous du seuil de détection de nos instruments de mesure pour le Pb (<4 ppm) et pour l'Ag. Les

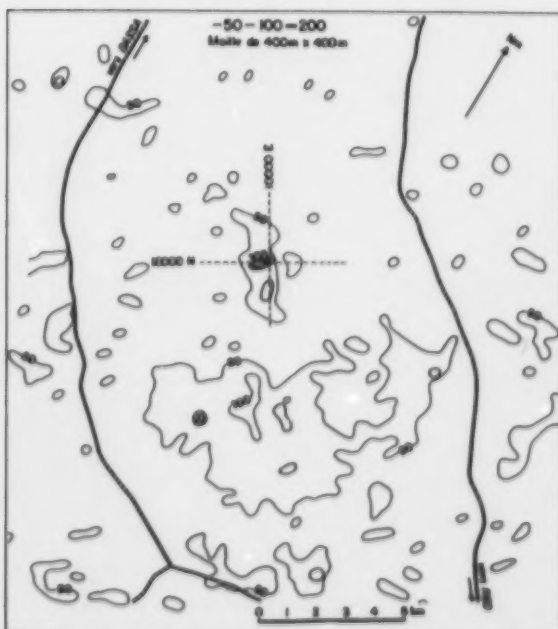


Figure 75.5. Géochimie régionale (Zn) autour du gisement de Perkoa. Valeurs en ppm (d'après PNUD 1984).

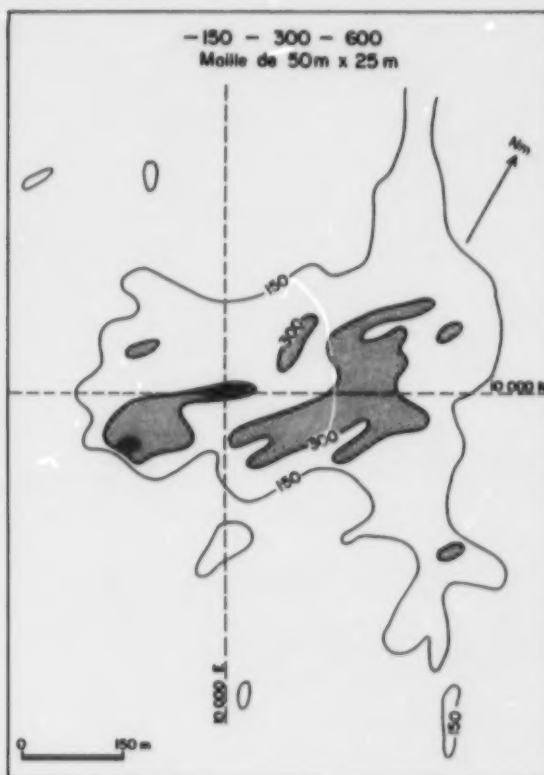


Figure 75.6. Géochimie détaillée (Zn) autour du gisement de Perkoa. Valeurs en ppm (d'après PNUD 1984).

teneurs au dessus du gisement ne se retrouvent pas dans les sondages et le rapport Zn/Pb, qui est souvent inférieur à l'unité dans l'échantillon de sol (30 cm), dépasse largement 10 dans les sondages.

Les formations alluvionnaires, à l'Ouest de l'anomalie principale (Figure 75.3), se marquent par des teneurs élevées en Cu et en Mn. Ces alluvions proviennent en majeure partie de la chaîne de collines de Sangye, à environ 5 km au SE, où ont été trouvées plusieurs anomalies en Cu.

Les affleurements marquant le sommet du gisement (Figure 75.3) sont constitués de tufs schisteux minéralisés, de roches siliceuses (jaspolites) ou de roches ferrugineuses. Les teneurs maximales qui y ont été relevées sont de 12 000 ppm pour le Pb, de 5400 ppm pour le Zn, de 89 000 ppm pour le Mn, et de 112 ppm pour l'Ag.

## GÉOPHYSIQUE

### MAGNÉTOMÉTRIE

La magnétométrie a été la première méthode géophysique appliquée sur le gisement (Dakio 1982). Une grande surface a été levée par les équipes du BUMIGEB avec un équipement Geo-

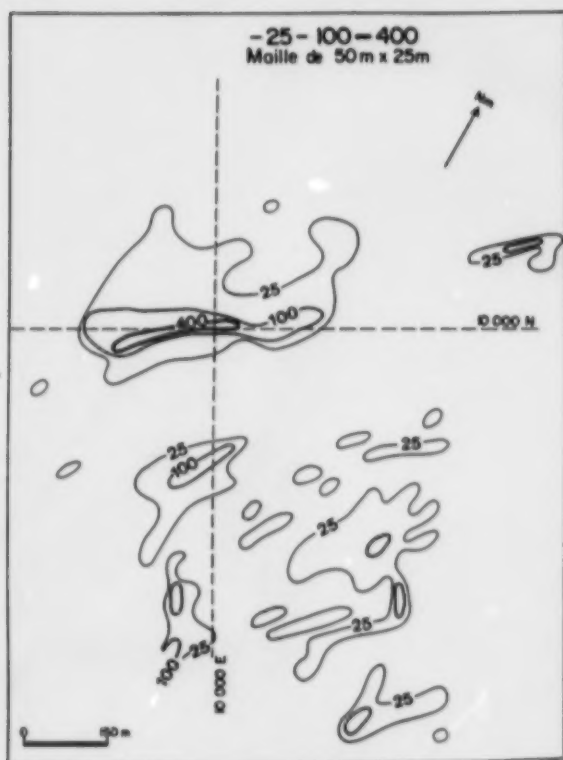


Figure 75.7. Géochimie détaillée (Pb) autour du gisement de Perkoa. Valeurs en ppm (d'après PNUD 1984).

metrics G816. L'étude dépasse largement les limites de la Figure 75.8. La maille de mesure est de 25 par 25 m autour de l'anomalie principale et de 25 par 50 m sur le reste de la carte. Comme on le voit sur la Figure 75.8, une anomalie très nette se dessine au-dessus du corps minéralisé avec un minimum de 140 nT au NNE et un maximum de 80 nT au SSW.

Ce contraste de 220 nT n'est certainement pas dû à l'aimantation induite seule, car, comme on le voit, l'anomalie n'est pas exactement NS et elle présente de plus un positif important qui n'est pas compatible avec l'aimantation induite sous ces latitudes (12°). Nous sommes donc obligés de faire intervenir une part d'aimantation rémanente.

Si nous appliquons la méthode préconisée par Schnetzler et Taylor (1984), nous arrivons aux valeurs suivantes:

- déclinaison d'aimantation entre 30° et 60°
- inclinaison entre 0° et 30°

Paterson *et al.* (1985) nous indique qu'il a dû utiliser une inclinaison anormale de 38.5° pour ajuster les valeurs calculées et les mesures de terrain. Il arrive ainsi au modèle suivant au niveau du profil 9950E (Figure 75.9):

- Profondeur : 43 m
- Largeur : 66 m
- Longueur : 1000 m
- Epaisseur : 172 m
- Pendage : 72°N
- Susceptibilité : 0.0032 uem

Ces paramètres sont en accord avec les résultats ultérieurs acquis par les sondages et les mesures de

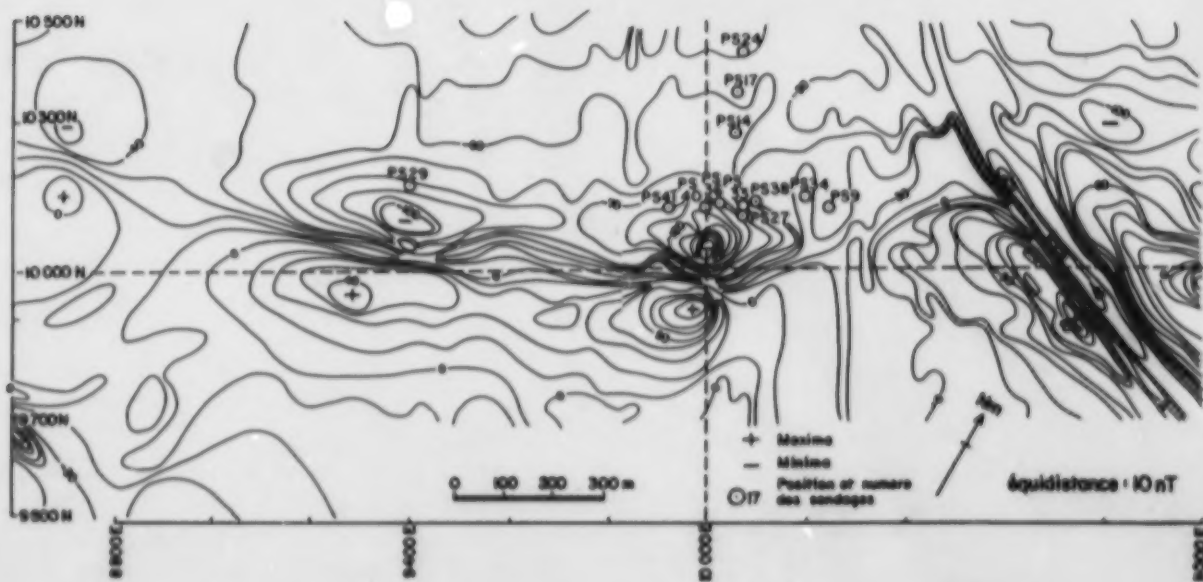


Figure 75.8. Anomalie magnétique (champ total) autour du gisement de Perkoa (d'après Pennaroya 1986).

### Modèle utilisé (TAB2)

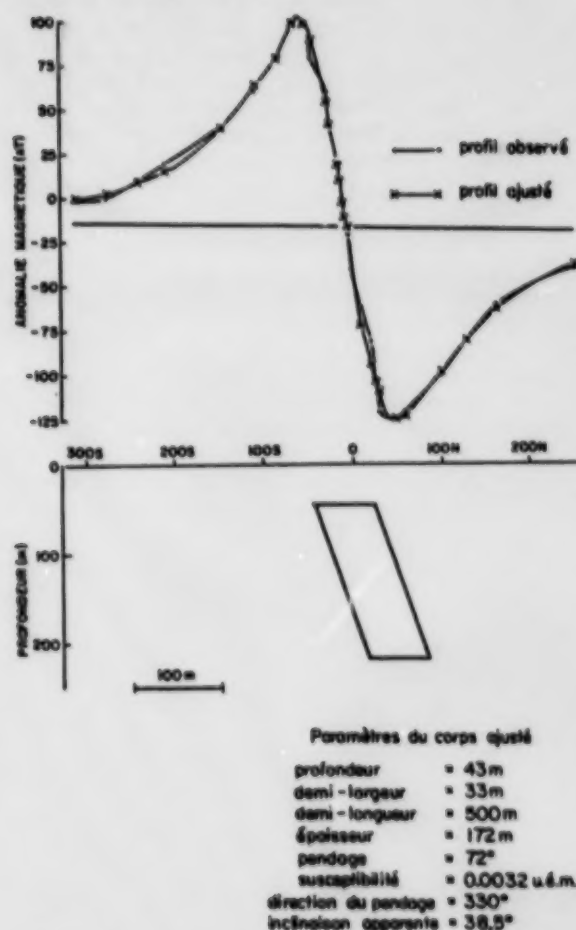


Figure 75.9. Modèle magnétique du corps de Perkoa (district du Reo) selon la cote 9950E (d'après Paterson, Grant and Watson Limited 1985).

susceptibilité effectuées sur les carottes (Figure 75.10). Seule l'épaisseur est un peu pessimiste, le corps d'intérêt économique ayant été recoupé par des sondages jusqu'à une profondeur de 450 m. La largeur, quand à elle, est très variable car le corps est fortement "boudiné" (Pennaroya 1986). Notons que la longueur indiquée par Paterson *et al.* (1985) comprend le gisement de Perkoa plus la première anomalie magnétique située à l'WSW.

L'anomalie est due en majeure partie à la présence de pyrrhotine qui apparaît sous forme de feuillets continus ou d'aggrégats et dont la teneur se situe, d'après les valeurs de susceptibilité, aux alentours de 10 pourcent (Paterson *et al.* 1985). Toujours d'après Paterson *et al.* (1985), les mesures du champ magnétique total prises en volant au-dessus de Perkoa (150 m) devraient accuser une forte

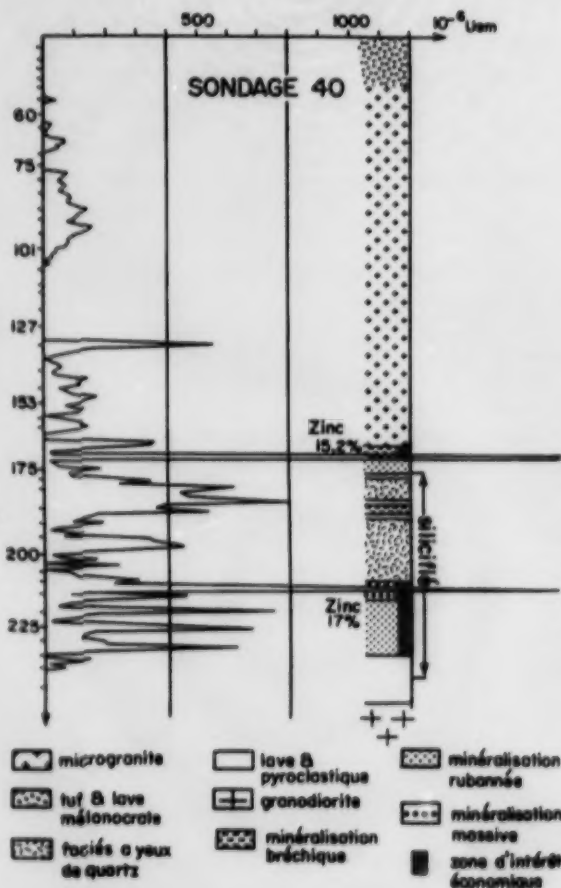


Figure 75.10. Valeur de la susceptibilité dans le sondage 40 (d'après Mage 1988).

baisse d'amplitude, jusqu'à atteindre 31 nT. Ceci implique que les anomalies relativement faibles décelées par levé aéroporté doivent être prises en considération.

L'anomalie située à l'WSW au niveau du profil 9400E, a été sondée et a donné les mêmes caractéristiques géologiques que le gisement principal, sauf que la minéralisation d'intérêt économique n'existe plus. Ici aussi, l'anomalie est causée par la pyrrhotine.

D'autres cibles ont été sondées pour leur réponse magnétique mais, sauf pour une qui renfermait de la pyrrhotine, le minéral responsable était la magnétite.

### ELECTROMAGNÉTISME

#### Domaine Fréquence

Deux appareillages EM en domaine fréquence ont été utilisés sur Perkoa: un Geonics EM 17 et un Apex Parametrics Max-Min II. L'EM 17



(1600 Hz) a été employé en premier (Dakio 1982). S'appuyant sur ces résultats, on pouvait penser que les méthodes électromagnétiques ne donnaient pas d'anomalies significatives à Perkoa (Paterson *et al.* 1985). Par la suite (IWACO 1983), un profil test a été mesuré avec un appareillage Max-Min. On s'aperçut alors qu'une réponse discriminatoire commençait à apparaître vers 888 Hz et devenait de plus en plus apparente à mesure que la fréquence diminuait (444 et 222 Hz (Figure 75.11)).

L'altération à Perkoa, comme dans une bonne partie de l'ensemble du pays, est assez épaisse ( $\pm 40$  m) et passablement conductrice. Quand on emploie des fréquences plus élevée que 888 Hz, le rapport signal/bruit devient très mauvais et il est impossible de différencier le grand nombre d'anomalies en présence: faille, altération différentielle du bedrock, ou sulfures conducteurs? Par contre, des fréquence plus basses permettent de traverser aisément cette altération et de ne plus prendre en considération que les anomalies conductrice se trouvant dans la roche saine.

Cette fréquence de 1600 Hz avait été utilisée à l'époque car l'EM 17 était le seul appareil EM disponible au BUMIGEB.

Après l'analyse des résultats, on pouvait dire qu'un corps réagissant comme un conducteur continu, plongeant fortement vers le NW et dont l'axe

des courants induits se trouve vers 60 m de profondeur, apparaissait à Perkoa (IWACO 1983).

L'axe de l'anomalie EM est parfaitement corrélé avec l'axe de l'anomalie magnétique. La pyrrhotine est donc là aussi certainement responsable et représente le conducteur continu. Par la suite (Mage 1987), une étude plus poussée en EM domaine temps a permis de mieux connaître les caractères physiques du corps.

#### Domaine Temps

##### a) Moving Coil

Un appareillage Crone Pem a été utilisé. Les caractéristiques techniques utilisées sont: time = 10 ms, ramp = 1.0 ms,  $T_x R_x = 100$  m. On voit avec les différents profils effectués sur et autour du gisement de Perkoa (Figure 75.12) que l'anomalie PEM est comprise entre les profils 9200E et 10 200E, avec un maximum sur le profil 10 000E, cote 10 000, et un autre sur le profil 9400E, cote 10 050. Le reste de la région est particulièrement stable, et l'absence de bruits parasites nous montre l'excellent rapport signal/bruit.

L'analyse des huit canaux (Figure 75.13) levés le long du profil 10 000E montre les caractéristiques suivantes pour le conducteur (d'après Bartel and Hohman 1985)

- Position : 9990
- Largeur : 25 m

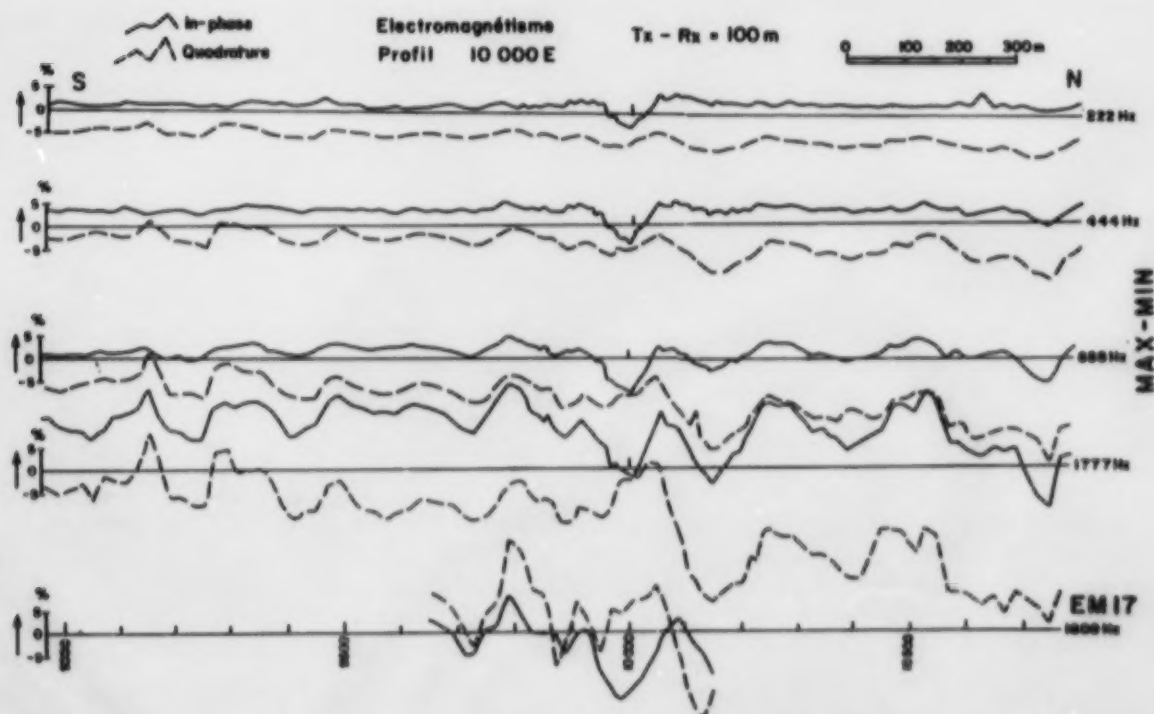


Figure 75.11. Profil E-M (domaine fréquence) (Perkoa) selon la cote 10 000E (d'après IWACO 1983; Dakio 1983).

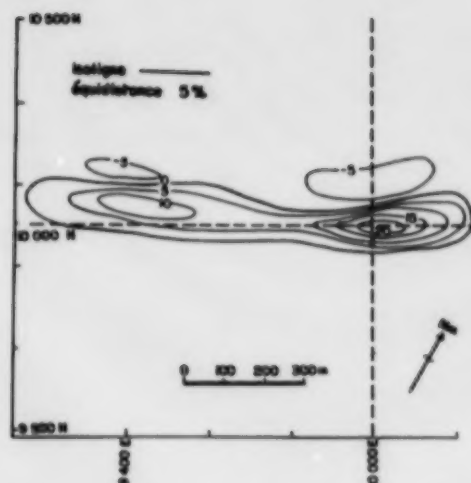


Figure 75.12. Champ électromagnétique secondaire autour du gisement de Perkoa. Crone PEM, canal 6 (d'après Mage 1988).

- Pendage : 70°NW
- Profondeur du toit : 30 m
- Conductivité • épaisseur : 70S
- Direction du corps : N225E
- Profondeur de l'altération : 35 m
- Nombre de canaux anomaux : 8

La réponse amoindrie des canaux 1 et 2 s'explique du fait de l'altération. L'anomalie qui apparaît à la cote 10 135 et sur deux canaux seulement représente un phénomène très près de la surface et n'est pas directement intéressant au plan minier. Au vu des résultats des différents sondages qui ont été effectués à Perkoa (Figure 75.4), on peut admettre que l'anomalie EM n'est pas due à un conducteur massif simple, mais plutôt à une succession de feuillets de pyrrhotine, parallèles entre eux, sur une largeur de 20 à 25 m. Ces feuillets sont continus, au sens électrique du terme.

Quand on regarde la réponse de la deuxième anomalie située sur le profil 9400E (Figure 75.14), on est étonné de la similitude des courbes. Seuls les trois premiers canaux sont nettement plus affectés par les phénomènes d'altération superficielle, qui semble plus conductrice. Les caractéristiques du corps sont les suivantes:

- Position : 10 035
- Largeur : 20 m
- Pendage : 70°NW
- Profondeur du toit : 35 m
- Conductivité • épaisseur : 70S
- Direction du corps : N235E

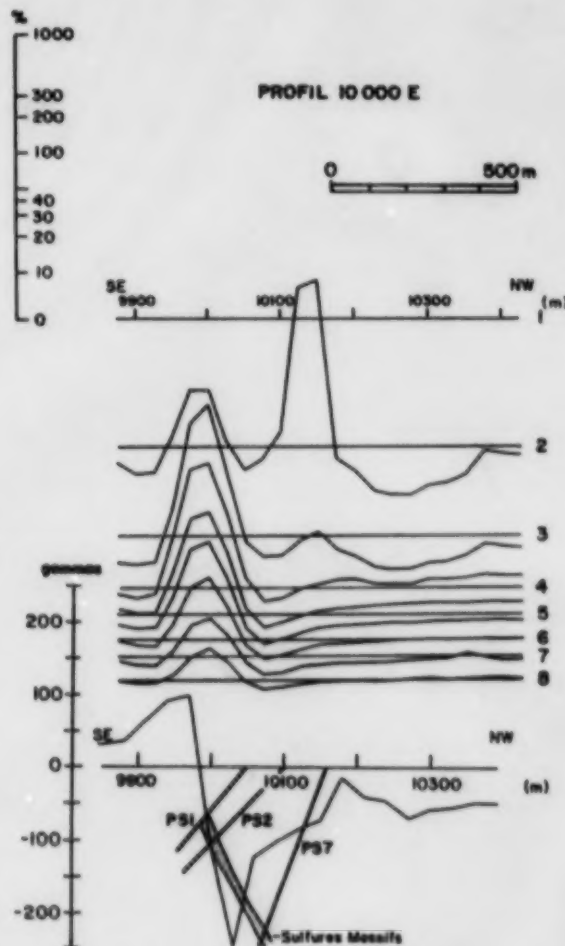


Figure 75.13. Réponse des 8 canaux du Crone PEM et du magnétisme sur le gisement de Perkoa, selon la cote 10 000E (d'après Mage 1988; Dakio 1982; PNUD 1984).

- Profondeur de l'altération : 45 m
- Nombre de canaux anomaux : 8

Cette anomalie a été sondée mais n'a montré aucune teneur économique.

Comme on pouvait s'y attendre, la présence ou l'absence de blende ne se marque absolument pas dans la réponse EM et seule la gravimétrie peut différencier la réponse. L'EM nous permet par contre de discriminer les différentes anomalies magnétiques. En effet, la magnétite, dans la région de Perkoa en tout cas, ne donne des anomalies EM que sur trois à quatre canaux, alors que la réponse de la pyrrhotine se marque sur huit canaux, indiquant par là un bien meilleur conducteur. Cela vient du fait que la pyrrhotine se présente en feuillets, alors que la magnétite est sous forme d'aggrégats, empêchant ainsi une bonne connexion électrique entre les grains.

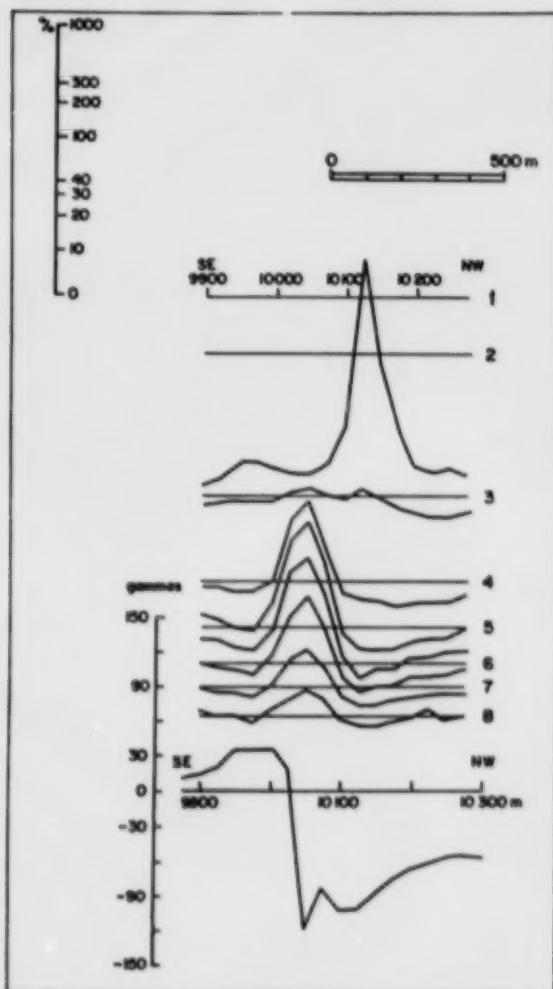


Figure 75.14. Réponse des 8 canaux du Crone PEM et du magnétisme sur l'anomalie satellite de Perkoa, selon la cote 9400E (d'après Mage 1988; Dakio 1982).

#### b) Deepem

Plusieurs profils de type Deepem ont été levés sur le gisement de Perkoa. L'impulsion émise est envoyée par une boucle carrée de 100 par 100 m ou de 300 par 300 m. Les caractéristiques utilisées sont les mêmes que pour le Moving Coil en ce qui concerne la durée de l'impulsion et le temps de chute du courant. Sur la Figure 75.15, la boucle émettrice est située au sud-est du gisement, alors que pour la Figure 75.16 elle est au nord-ouest. On voit tout de suite que la réponse est bien meilleure sur la Figure 75.15, confirmant par là un pendage vers le nord-ouest qui donne un couplage accru avec le champ primaire. La différence de position des courants tourbillonnaires (9990 pour la Figure 75.15 et 10 000 pour la Figure 75.16) nous donne une idée de

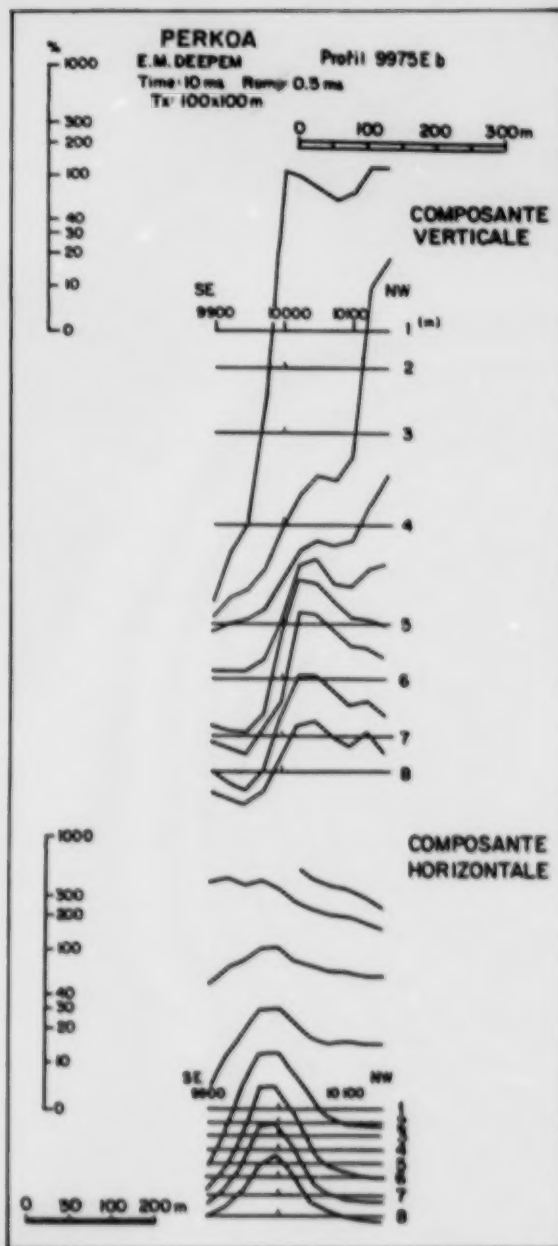


Figure 75.15. Réponse des 8 canaux du Crone Deepem sur le gisement de Perkoa, selon la cote 9975E. La boucle d'envoi de courant est au SE (d'après Mage 1988).

l'épaisseur minimale du conducteur (ici 10 m), alors que leur profondeur (30 m) nous indique à quel niveau maximum nous allons trouver le corps responsable.

La profondeur de pénétration du Deepem étant plus importante que pour le Moving coil, on en déduit que la conductivité du corps augmente avec

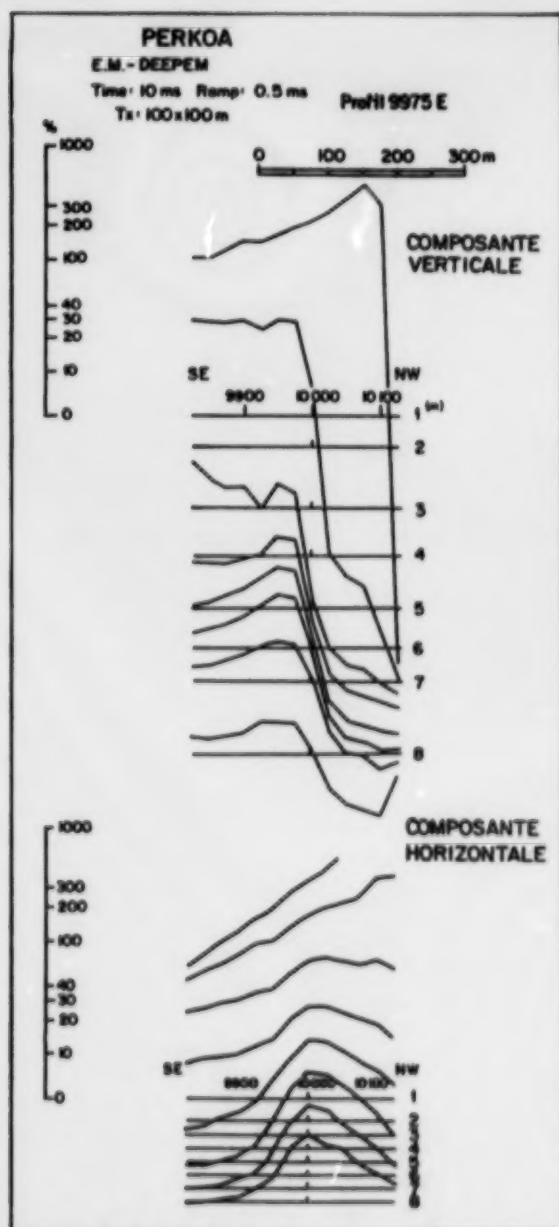


Figure 75.16. Réponse des 8 canaux du Crone Deepem sur le gisement de Perkoea, selon la cote 9975E. La boucle d'envoi de courant est au NW (d'après Mage 1988).

la profondeur. La réponse est très fortement amoindrie sur les canaux 1 à 3 quand on emploie une boucle d'envoi de courant de 100 par 100 m (Figures 75.15 et 75.16). Lorsqu'on utilise une boucle encore plus grande (300 par 300 m, Figure 75.17), aucune anomalie n'est visible dans les cinq premiers canaux. Cela provient du fait (Crone, Géophysicien, Crone Geophysics Limited, Missis-

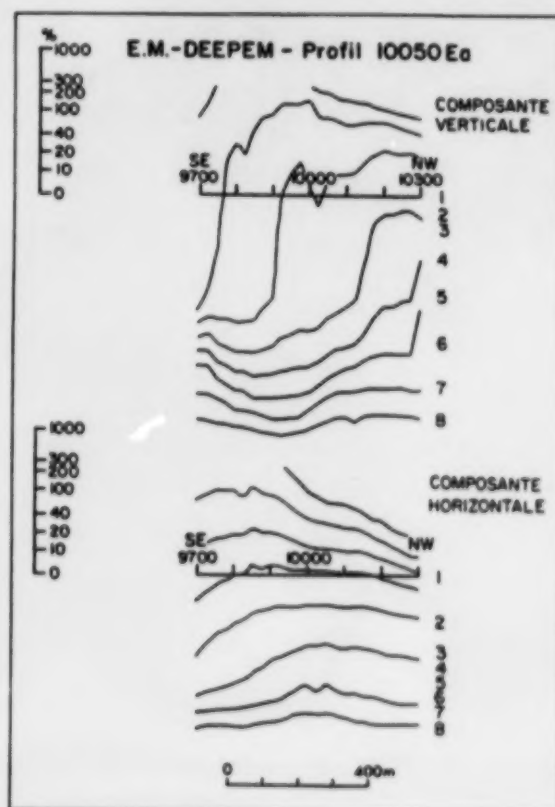


Figure 75.17. Réponse des 8 canaux du Crone Deepem sur le gisement de Perkoea, selon la cote 10 050E. La boucle d'envoi de courant est de 300 par 300 m (d'après Mage 1988).

sauga, Ontario, communication personnelle, 1987) que le volume du recouvrement conducteur devient de plus en plus grand, ralentissant ainsi la réponse du conducteur métallique par absorption d'une partie de l'énergie.

Pour un corps du type Perkoea, se situant près de la surface, les levés de type Deepem n'apportent que peu de renseignements supplémentaires, mais peuvent servir à confirmer l'interprétation. Il en serait tout autrement si le sommet du conducteur était plus profond.

### Polarisation Provoquée

#### Gradient Array

Une configuration gradient a été employée au début sur Perkoea, en utilisant un appareillage Huntect, domaine "temps". Les caractéristiques géométriques sont: AB = 1000 m, MN = 20 m, pas de 20 m.

La carte de chargeabilité nous montre très bien les contours du gisement (Figure 75.18), représenté par une chargeabilité de 12 (mV/V) pour un fond de 5 (mV/V), soit deux fois et demi plus élevé.



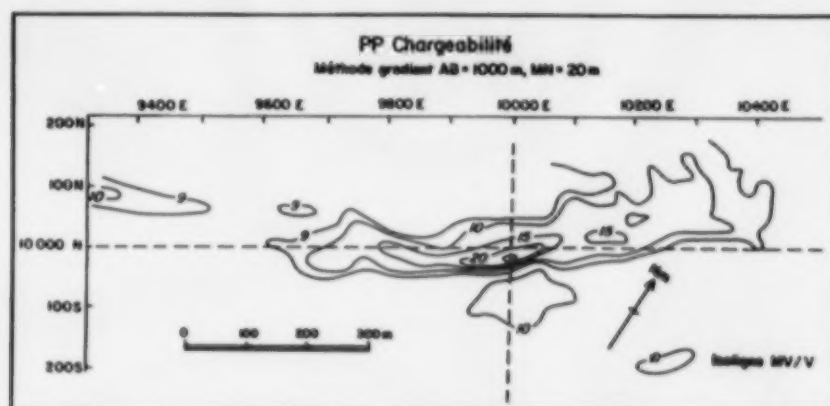


Figure 75.18. Anomalie en chargeabilité autour de gisement de Perkoa (d'après Dakio 1983).

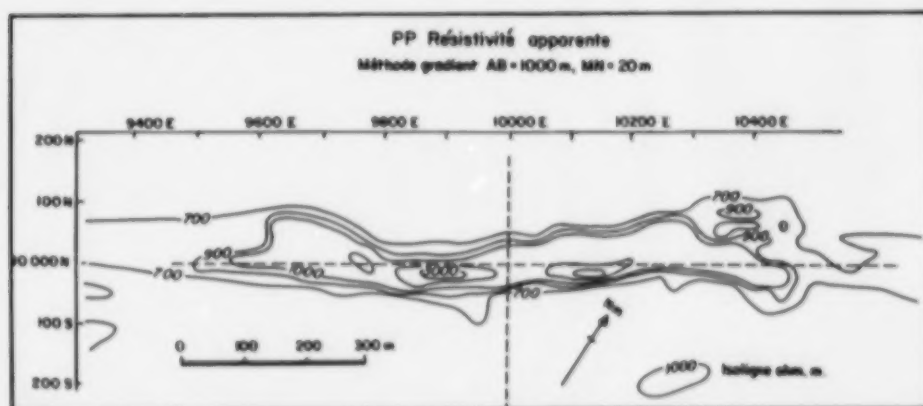


Figure 75.19. Anomalie en résistivité autour du gisement de Perkoa (d'après Dakio 1983).

La carte de résistivité (Figure 75.19) nous indique par contre une zone résistante à l'aplomb du gisement, atteignant environ quatre fois la valeur du fond régional qui est de 400 ohm-m. Ces mesures élevées proviennent de deux causes: d'abord le gisement est constitué essentiellement de blende, c'est-à-dire d'un minéral non conducteur, ensuite il est pris dans une gangue siliceuse. Cela explique le fait que la zone soit résistante. Elle est aussi chargeable, et nous pensons que, cette fois, l'anomalie en chargeabilité n'est pas due seulement à la pyrrhotine mais que la présence de pyrite en grains peut en expliquer une large part. Le dipôle-dipôle effectué va nous donner plus de renseignements.

#### Dipôle-Dipôle Array

Pour cette configuration un appareillage Scintrex, domaine "temps" a été utilisé. Les caractéristiques techniques sont  $a = 50$  m,  $n = 6$ .

Quand on regarde les pseudo-sections pour la résistivité et la chargeabilité (Figure 75.20), on s'ap-

perçoit que l'anomalie en chargeabilité se situe autour de la cote 9970 alors que l'anomalie en résistivité a son centre à la cote 10 020. On doit donc imaginer un modèle de deux corps parallèles entre eux, ceux-ci plongeant vers le Nord comme l'examen des courbes le montre. En allant du Nord au Sud, on trouve d'abord 40 m d'une roche résistante, non chargeable, puis de nouveau une quarantaine de mètres d'une roche contenant des minéraux réagissant à la polarisation provoquée. En analysant les différents sondages effectués sur Perkoa (Figure 75.4), on s'aperçoit que ceux-ci, inclinés vers le Sud, ont d'abord rencontré une roche fortement silicifiée, puis la minéralisation, elle aussi passablement silicifiée quand elle n'est pas massive. Cette silicification de la minéralisation augmente la résistivité de la roche totale, ce qui explique pourquoi on ne trouve pas une bonne conductivité (en P.P.) sur le gisement ni autour (Figure 75.19).

Quand on essaie d'interpréter ces données (Figure 75.21), on s'aperçoit qu'un modèle de dyke ver-

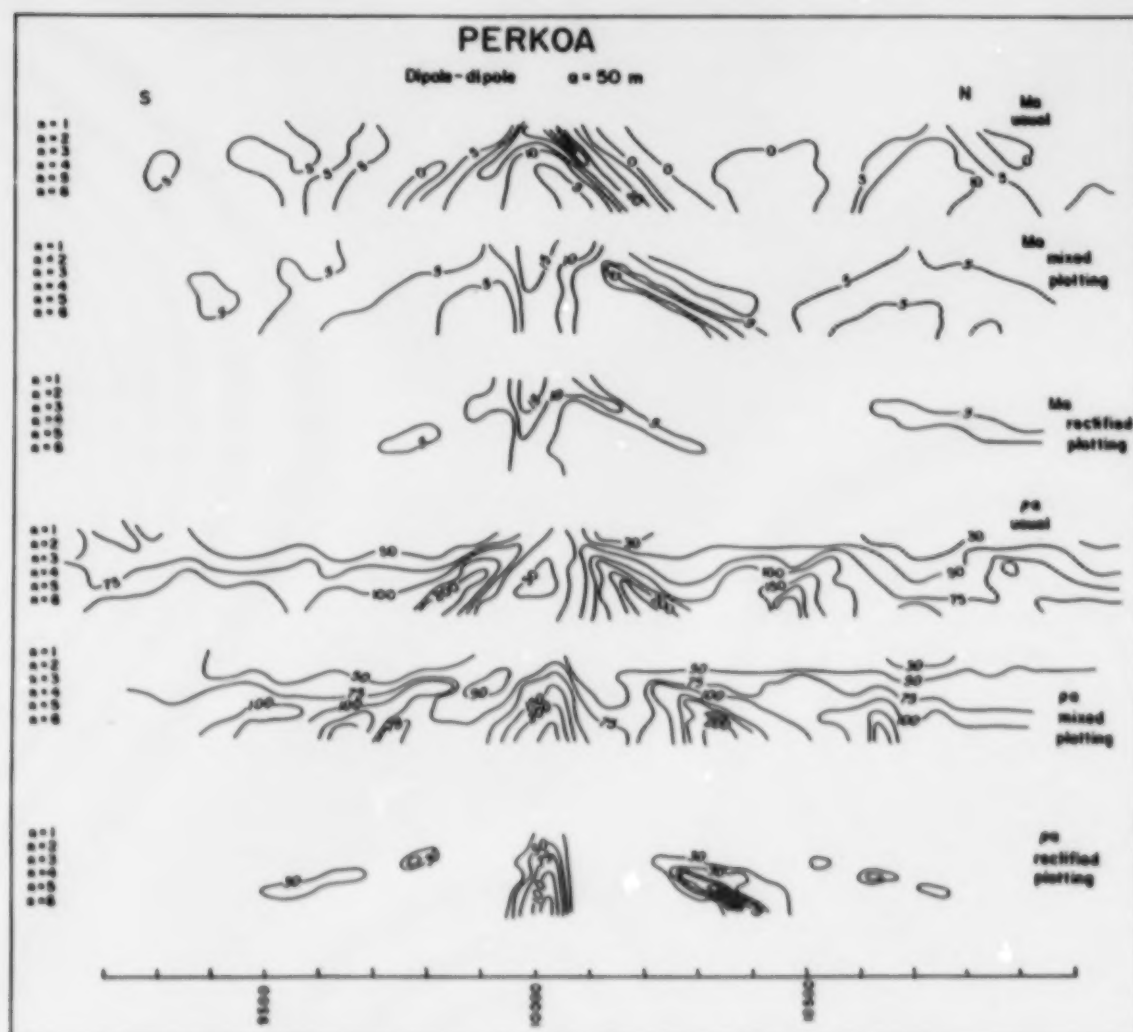


Figure 75.20. Réponse en dipôle-dipôle (chargeabilité et résistivité) sur le gisement de Perkoa selon la cote 10 000E (d'après Dakio 1983).

tical ayant 40 m de large, une résistivité de 1000 ohm-m et situé entre les cotes 10 000 et 10 040, donne partiellement la même réponse en résistivité que celle mesurée sur le terrain. On doit néanmoins apporter deux corrections majeures:

- faire pencher ce dyke vers le Nord afin d'augmenter les valeurs de la résistivité de ce côté

- changer la valeur pour l'encaissant, qui avait été choisie avec une moyenne de 45 ohm-m, pour lui donner une valeur de 30 ohm-m en surface et qui augmente progressivement jusqu'à 100 ohm-m vers 80 m de profondeur. Remarquons que ces valeurs basses pour la résistivité sont typiques de la couverture des régions de l'Afrique de l'Ouest.

En essayant de donner un modèle de dyke vertical pour interpréter le corps sensible à la stimulation par polarisation provoquée, on arrive aux mêmes conclusions concernant le pendage. La position du modèle se situe entre 9950 et 9990. On lui a donné ici une valeur de 30 mV/V qui semble raisonnable. Comme les mesures négatives n'existent pas sur le terrain, on ne peut faire affleurer ce corps et on est obligé de l'enfoncer jusqu'à une profondeur de 30 m. De plus, les courbes se ferment vers le bas au lieu de s'ouvrir comme pour la résistivité. On doit ainsi donner une extension limitée vers le bas ou, en tout cas, un rétrécissement.

Cette hypothèse est confirmée par les sondages (Figure 75.4), si on admet que la minéralisation

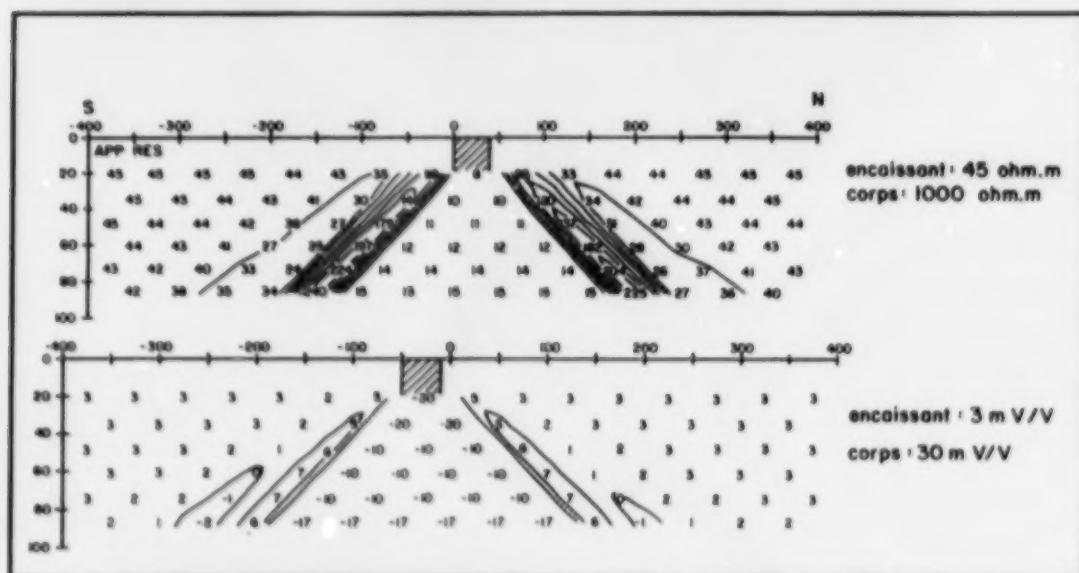


Figure 75.21. Réponse d'un dyke en dipôle-dipôle (programme S. Edwards, PNUD, Manille).

rubannée est responsable de l'anomalie en chargeabilité. L'encaissant réagit différemment au Sud (6 mV/V) qu'au Nord (1 mV/V). Les sondages ont montré la présence de la granodiorite en contact avec la partie Sud du gisement. Celle-ci est vierge de grains métalliques et peut difficilement expliquer l'augmentation de l'effet polarisation provoquée. On doit donc imaginer une polarisation de membrane due à des minéraux d'altération de nature différente au-dessus de la granodiorite par rapport à ceux se trouvant au-dessus des laves. En l'absence de sondage au Sud du gisement, la question reste posée.

#### Gravimétrie

Pour la gravimétrie, un appareillage Lacoste et Romberg a été utilisé sur une grille de 20 x 20 m.

La gravimétrie a été testée sur une petite surface autour du gisement. Quatre anomalies positives apparaissent (Figure 75.22). Leur amplitude est de l'ordre de 0.15 mgals. Quand on compare les résultats avec la carte des anomalies magnétiques (Figure 75.8), on s'aperçoit que seule l'anomalie sur le gisement apparaît à la fois en gravimétrie et en magnétométrie. Ceci est dû à la présence de blende et de pyrrhotine. La première anomalie secondaire, à l'Ouest, correspond à un petit amas de blende. L'anomalie nord ne montre aucune minéralisation et peut être expliquée par une montée de la roche saine visible dans les sondages. L'anomalie au NW n'a pour le moment pas été sondée, mais est certainement due aussi à une remontée du bedrock.

Les mesures ont été levées jusqu'à la deuxième anomalie magnétique d'importance, mais ne

montrent aucun changement de densité particulier dans la composition des roches sous-jacentes. A cet endroit, le sondage 29 a montré la présence de pyrrhotine en feuillets, mais la blende y est absente, ce qui explique le faible contraste de densité.

#### Polarisation Spontanée (Figure 75.7)

Une large zone a été couverte par polarisation spontanée mais n'a donné aucune anomalie caractéristique. A titre d'exemple, nous présentons ici un profil effectué sur le gisement principal (Figure 75.23). Comme on le voit, les mesures ne dépassent pas une dizaine de mV. Le corps de Perkoa n'aurait pu être découvert par ce moyen.

#### CONCLUSIONS

Comme nous avons pu le voir, la géophysique montre des réponses très claires à Perkoa, malgré l'épaisseur du recouvrement (Figure 75.24). Le magnétisme et l'électromagnétisme donnent chacun un rapport signal/bruit élevé et ces méthodes devraient être employées plus systématiquement dans ces régions. En effet, la géochimie régionale qui a été effectuée au Burkina Faso n'a montré des anomalies que dans les endroits où la roche affleure. Il est donc logique de penser qu'une partie au moins des anomalies sont cachées par l'épaisseur du recouvrement. Les méthodes géophysiques aéroportées semblent ainsi particulièrement indiquées de par leur coût relativement faible par rapport à la surface couverte et de par leur profondeur d'investigation qui peut atteindre une centaine de mètres, même avec un recouvrement conducteur. Un tel levé est en cours d'exécution depuis novembre 1987

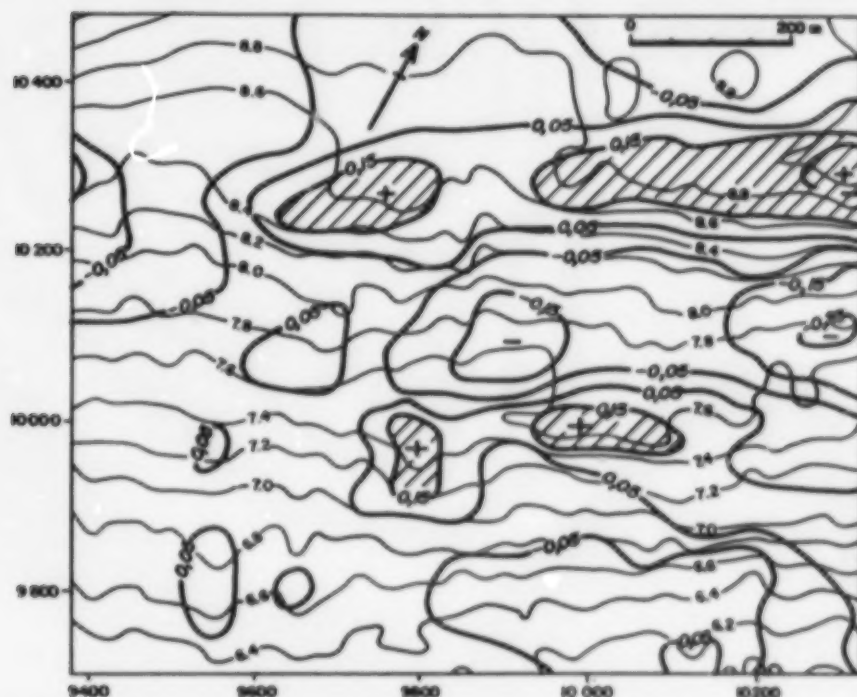


Figure 75.22. Anomalie de Bouguer ( $d=2.5 \text{ g/cm}^3$ ) et anomalie résiduelle (ordre 2) autour de Perkoa, valeurs en mgals (d'après Braban 1984).

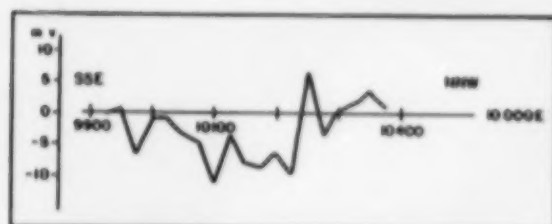


Figure 75.23. Réponse en polarisation spontanée sur le gisement de Perkoa, selon la cote 10 000E (d'après Dakio, non publié).

en magnétométrie et électromagnétisme pulsé avec un espacement des lignes de vol de 250 m.

Le BUMIGEB possédant maintenant un gravimètre, cette méthode pourrait aussi être employée sur les cibles choisies.

Le gisement de Perkoa peut se définir de par ses caractères géophysiques comme un corps résistant, chargeable et qui, de part les feuillets de pyrrhotine qui le parcourent, réagit aussi comme un conducteur face aux méthodes électromagnétiques. Notons que si ces feuillets de pyrrhotine n'étaient pas là, il aurait été fort malaisé de le mettre en évidence, et par l'EM et par la magnétométrie. Ainsi les indices de Goren (Cu + Mo et pyrite) et de Koupéla-Nagsene

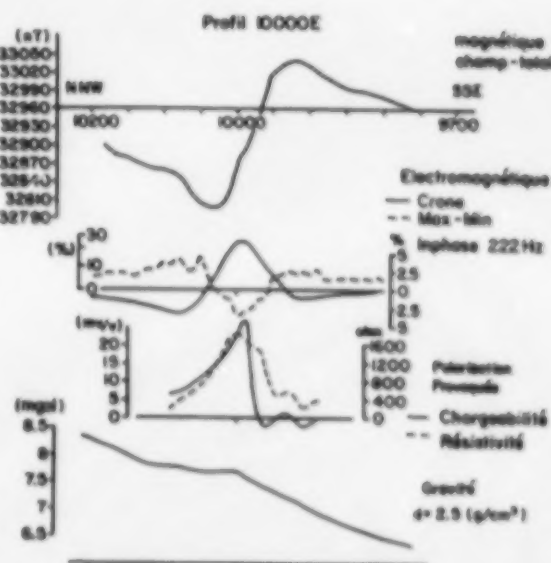


Figure 75.24. Réponse de différentes méthodes géophysiques sur le gisement de Perkoa, selon la cote 10 000E.



(Zn, Pb, Au + pyrite) n'ont montrés des anomalies en géophysique qu'avec la polarisation provoquée; le magnétisme et l'EM ne donnant rien et la gravimétrie n'ayant pas encore été utilisée sur ces sites.

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Nous sommes également reconnaissants à Minorex et Pennaroya pour leurs informations concernant Perkoa.

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## 76. Case History of a Kimberlite Discovery, Wajrakarur Area, A.P., South India

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### ABSTRACT

A new kimberlite was found in December 1985 in an area in Andhra Pradesh, South India, where six other kimberlites had been discovered earlier. Although this region has been known for a long time for frequent finds of diamonds at the Earth's surface, nothing is definitely known about the source kimberlites from which these diamonds may have been derived. An integrated research-type study of this region which resulted in the above-mentioned discovery, revealed that there are large-scale faults in this part of the crust, some of which may have had a role in localizing the kimberlite emplacements. Morphological studies revealed that gravels in the area, in which diamonds are frequently found, are perhaps multicycle deposits and do not necessarily indicate proximal kimberlites. The nature and distribution of the location of diamond finds in this area has given rise to widespread belief that there must be more kimberlites in this area which have not yet been located. It is concluded that the most promising tool for searching for more kimberlites in this area is the method of stream gravel sampling for specific indicator minerals. Where there is a soil cover, and the streams may not be effective in concentrating heavy indicator minerals, electromagnetic induction and magnetic mapping should succeed in locating weathered kimberlites.

### INTRODUCTION

There are two regions in India where kimberlites are known to occur. One is in central India near the town of Panna in Madhya Pradesh, and the other in south India near the village of Wajrakarur in Andhra Pradesh. This paper deals with the discovery of a new kimberlite in the southern zone. This area has a history of large-scale diamond mining in alluvial deposits, and is reported to have produced two of the best known diamonds, namely the Kohinoor, and the Regent. The concentration of diamonds in the known kimberlites, however, does not seem to account for such large alluvial deposits, or to explain the fact that in this area, diamonds are frequently picked up at the surface over a very large stretch of ground (Figure 76.1). There is widespread belief that there must be more kimberlites which have not been found yet.

The country rock in the area is a granite-gneiss in which there are a number of arcuate belts of greenschist, and some younger intrusive granites. The regional metamorphism has not gone beyond the amphibolite facies except near the margin of the Indian peninsula, where one finds granulites. The region, traversed by many basic dikes (some of which occur in swarms), is topographically uneven except where there is a cover of black soil, locally known as black cotton soil. It falls in a semiarid

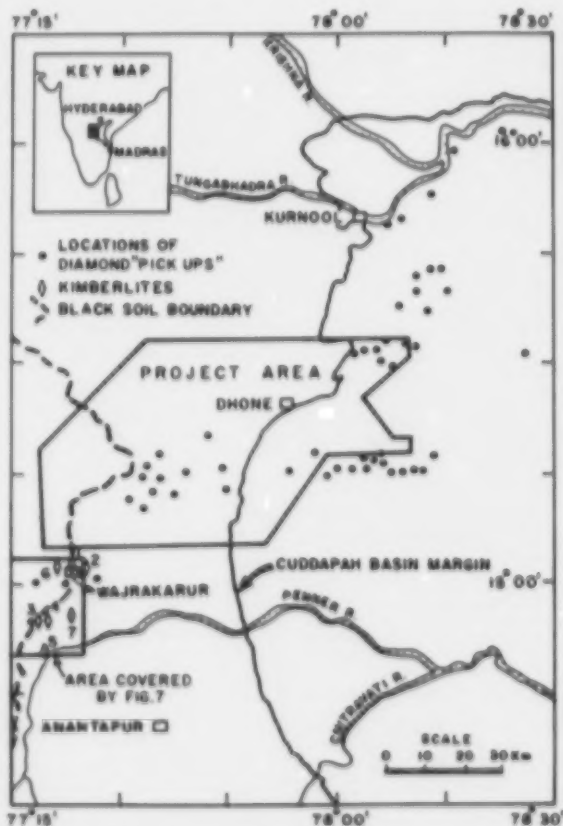


Figure 76.1. Location map showing the known kimberlites, diamond finds (after Sakuntala and Krishna Brahmam 1984), the project area, and the western margin of the Cuddapah Basin. The soil-covered area is to the west of the boundary shown.

zone where streams are mainly seasonal gullies which are active for about three months in the year during the monsoon season. The granitic basement is either exposed, under a thin weathered layer, or covered by black soil. It is quite magnetic, with a variable susceptibility, and its electrical conductivity is mainly controlled by the degree and state of local weathering. The schists are generally much more magnetic than the granite-gneiss, and grade into banded iron formations in some places. However, there are also chlorite-sericite and quartz schists which are weakly magnetic.

Finding kimberlites in this region is difficult for a number of reasons. One reason is that they are quite small in size; another is the absence of any definite physical property contrast with the surrounding rocks. The last discovery before the one reported herein was made by the Geological Survey of India (GSI) in 1968-1969 on the basis of a weak gravity anomaly. This was the sixth kimberlite in the area. Of the earlier five kimberlites, Pipe 1 at the village of Wajrakarur was known from historical times as a source of diamonds. The other four were discovered in the course of systematic geological mapping by the Geological Survey of India (Murty *et al.* 1980). Historical reports of mining for diamonds show that the Banganapalle Formation, a conglomerate horizon within a Proterozoic sedimentary basin called the Cuddapah Basin (which is located to the east of the group of known kimberlites), was being mined extensively. The source of these diamonds must also have been in the vicinity.

Mineralogically, these kimberlites conform to the definition given by Clement *et al.* (1977). Compared to kimberlites of South Africa they are reported to be lean in the typical indicator minerals, namely, pyrope garnet, chrome diopside, and picro-ilmenite (Krishnamurthy 1981). The depth as well as the degree of weathering is highly variable. Pipe 6 is weathered down to more than 300 m, while Pipe 2, not far from it, is practically unweathered. The magnetic responses of these kimberlites are quite different from each other, some being more magnetic than the host rock, and others less. Careful gravity measurements by the GSI have shown highs over some and lows over others. DC electrical resistivity shows a positive anomaly over unweathered kimberlite, and negative over those which are partly weathered (Bose 1980). Ground gamma ray spectrometry also does not show any characteristic anomaly over the known pipes.

The problem of finding a workable method for locating kimberlite in this area was taken up in 1982 by the National Geophysical Research Institute (NGRI), Hyderabad, as part of a United Nations Development Program (UNDP) aided research program. This resulted in the discovery of one more kimberlite, and some guidelines for further exploration for kimberlites in the area.

## INITIAL EXPERIMENTS

The cluster of known kimberlites in the area appears to be oriented approximately along a northeast-southwest axis. They are within the currently eroding area, except Pipe 6, which is under 2 to 3 m of black cotton soil. The soil-covered area represents a peneplain that is roughly at 470 m elevation, and the rest of the area, which is somewhat rougher, represents various stages of erosion of this surface. In the currently eroding area, streams are thought to be dispersing the erosion products of the basement, and kimberlites if present. In the soil-covered area, no such dispersion was expected to be taking place. Thus, different strategies seemed to be necessary for the two types of ground. Samples of gravel from streams eroding some of the known kimberlites, manually panned to recover the heavy minerals, showed kimberlite indicators up to 600 m downstream from the source pipes. Examination of the material of the Banganapalle conglomerates also showed the presence of kimberlite indicator minerals. This showed that looking for indicator minerals as tracers could be used as a method of search. But it appeared that this would not work in the soil-covered areas where some other method was necessary.

Experiments over Pipe 6, the only one under soil cover, were then made with different ground geophysical methods. Examination of airborne magnetic data, air photos, and satellite images were considered necessary. The area initially chosen for such an integrated study is shown in Figure 76.1. The choice of the area was governed by the location of the known kimberlites, the Banganapalle old workings, and the large number of diamond "pick ups" in the area; and included what appeared to be the most likely region where some unknown kimberlites could occur. The western part of this area is under soil cover, and the eastern part represents the current erosion surface.

Pipe 6 had been earlier covered by gravity, magnetic, and DC resistivity measurements (Bose 1980). It was then covered by multifrequency Slingram, CRONE pulsed EM, and a new time domain EM system called GS-100 made in NGRI. The GS-100 uses a 50 m x 50 m loop, a 10 amp controlled current pulse drive, 18 time channels over 10 ms of decay and a software algorithm for the rejection of large amplitude impulsive noise. The frequency domain EM measurements (Figure 76.2) did not show the presence of the pipe in an unambiguous manner. Anomalies of the same type of comparable size were seen away from the kimberlites as well. In fact, this was seen to be the case for DC resistivity, magnetic, and gravity responses also. The fact that many resistivity, magnetic, and gravity anomalies comparable to the anomalies observed over known kimberlites could be seen all over the area, made all these methods unsuitable as primary search tools for kimberlites.



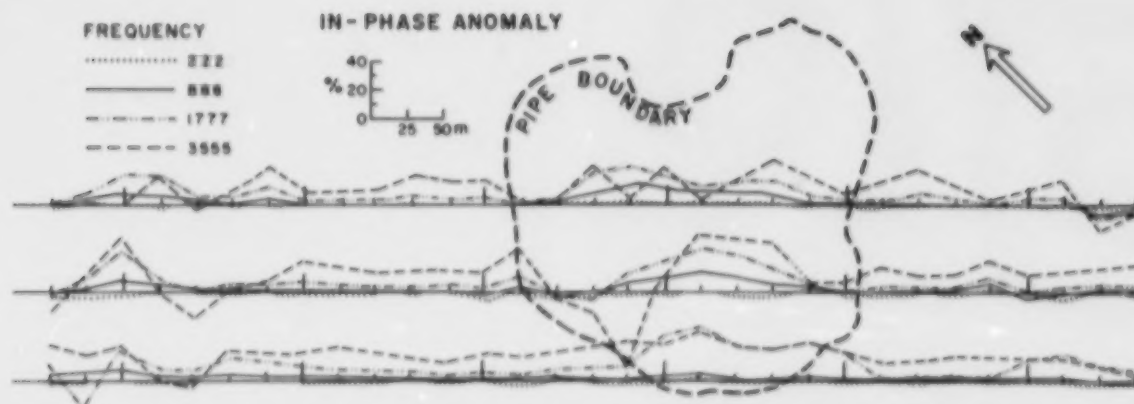


Figure 76.2. Pipe 6 is the only kimberlite in the area which is sufficiently weathered to produce recognizable EM response. This plot of MAXMIN II in-phase anomalies (source-receiver separation = 60 m) along three profiles intersecting pipe 6 shows that there is practically no response at the lowest frequency of 222 Hz. Response at 888 Hz is recognizable over the pipe, but comparable signals are also seen away from the kimberlite. Responses at higher frequencies are clearly due to near-surface conductivity variations.

The results of time domain EM were more encouraging (Figure 76.3). Response from the weathered kimberlite was strong, and persisted longer than the response from the soil-covered and weathered layer. Unlike the Slingram profiles, profiles of transient EM signal at appropriate values of time delay showed freedom from anomalies away from the kimberlite (Figure 76.2 and 76.3).

The advantage of time domain EM for this problem arises from the fact that in a soil-covered area, the currents induced in the near-surface conducting layer, composed of the soil and the underlying weathered bedrock, migrate away from the EM source with time while decaying in intensity. If, as in the case of a weathered kimberlite, the bottom of

this conducting layer extends downward into a more-or-less vertical body, the induced currents in this body, although decaying with time, are spatially restricted to stay within the body because the surrounding crystalline rock is highly resistive. As a consequence, it was found that there is a certain range of time along the decaying transient signal over which the signal-to-geological-noise ratio is high. At earlier times, the signal from the near-surface conducting material is strong and can mask the response of the kimberlite. At later times, the signal from the target has already decayed to values below the detection limit.

It is important to note that the above mechanism provides a means of qualitatively distinguishing be-

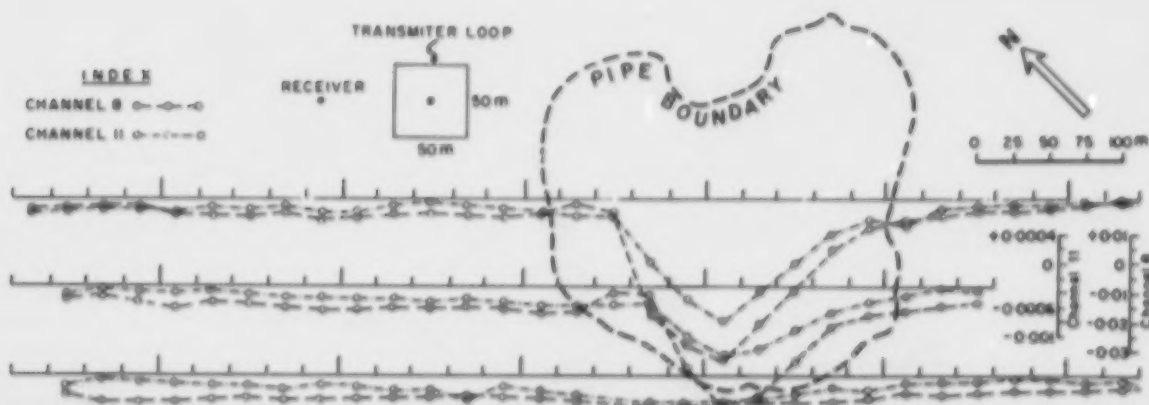


Figure 76.3. GS-100 profiles over Pipe 6, along the same traverse as Figure 76.2. Source-receiver separation was 75 m. Notice the strong response over the kimberlite and the remarkable freedom from clutter away from it. Channel 8 corresponds to a time window centred at 500  $\mu$ s, and Channel 11 at 1400  $\mu$ s, from the end of the source pulse.

tween response from the variable overburden and that from any laterally limited conducting body extending vertically below the weathered layer into the compact underlying basement. Such discrimination can be made, even when there is little or no difference between the conductivity of the surface material and the target. It is easy to see that no such local discrimination can be done by gravity, magnetic, DC resistivity, or continuous EM measurements.

VLF EM did not work on Pipe 6 because of the screening effect of the conducting soil cover. Total intensity magnetic traverses showed a dominant positive anomaly corresponding to a nonmagnetic target within surrounding magnetic rocks.

About 240 km² of soil-covered ground, partly within the project area and partly in the adjacent region to the south, were then traversed by GS-100 or CRONE PEM, and total intensity magnetic field measurements. The EM data did not bring out any anomaly comparable to that over Pipe 6, or over the soil-covered part of Pipe 1, although there were some weak anomalies. In addition, there were broad anomalies over areas of thicker soil/weathered layer, some of which could be due to old stream courses which are now buried under the black soil. Some of the weak EM anomalies were checked by pitting, but no kimberlite was found. There were many magnetic anomalies, but these were interpreted as due to magnetic schists, or to magnetic variations within the granite-gneiss basement under the soil.

Airborne magnetic data at a profile separation of 1/2 km was available over a large region covering the area chosen for detailed examination. The flight records of these profiles were examined and all anomalies which were suspected to be possible kimberlite targets were identified. Figure 76.4, which shows the magnetic anomalies over some known pipes while flying at different ground clearances, is an example of what was used to identify such possible targets. Of these anomalies, those which were associated with topographic lows, as shown by the airborne radio altimeter record, were graded as more important. A large number of anomalies were selected in this manner.

The aeromagnetic map (Figure 76.5) shows a large number of intersecting linears which occur primarily along faults in the Archean crust. Some of these are alignments along which dolerite dikes are emplaced, some are of quartz reefs, and others are due to zones of mylonitization along which the magnetite in the rock has been removed by some process not clearly understood. The aeromagnetic data, as well as detailed ground magnetic measurements, revealed one such near east-west magnetic linear comprising a dominant high in the total intensity, very close to Pipes 1 and 6 in the soil-covered area. Figure 76.6, obtained from ground magnetic measurements by applying a nonlinear smoothing filter and contoured at 50 gamma interval, clearly shows

this as well as some other northwest-trending features. Samples of the bedrock along the near east-west linear were found to be mylonitized granitic material with near zero magnetic susceptibility. In contrast, the susceptibility of the bedrock away from this zone ranges from 500 to 1500 x 10⁻⁶ cgs units.

Examination of air photographs of the area also revealed what appeared to be some possible targets. These locations were picked up on the basis of the shape of laterally limited features having a tonal contrast; radially converging drainage indicating a local circular or oval depression in the topography; short linears oriented in a northeasterly direction; and features near Landsat or aeromagnetic linears, or their intersections.

Magnetic anomalies related to such air photo features were considered more important than others. Such magnetic anomalies, as well as many air photo anomalies, were investigated by ground resistivity measurements, followed by pitting where considered necessary; but no kimberlite was found at any of these locations.

Approximately 800 gravel samples, 30 to 60 kg each, collected from streams in the area under examination were concentrated by manual panning, and examined for the presence of kimberlite indicator minerals. The sampling was done at a nominal

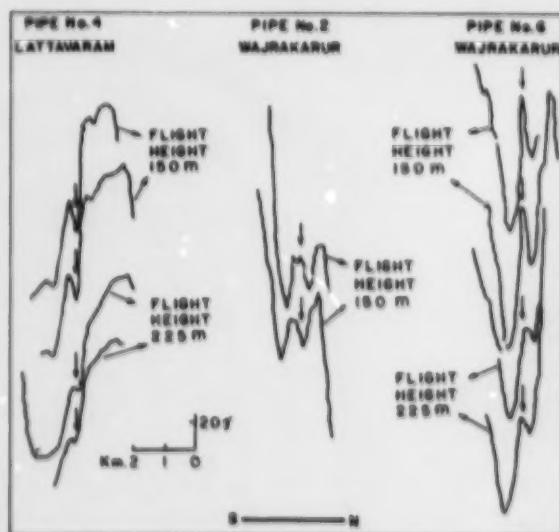


Figure 76.4. Special north-south test flights were made precisely over some of the kimberlites at ground clearances of 150 m and 225 m in order to find identifiable signatures in the magnetic responses. It turned out, however, that Pipe 4 showed a negative, Pipe 6 showed a positive and Pipe 2 showed a mixed response. Vertical arrows show the locations of the kimberlites. There were many such features in the magnetic profiles, but those which could be caused by small objects similar to the known kimberlites were suspected to be significant as possible new targets.

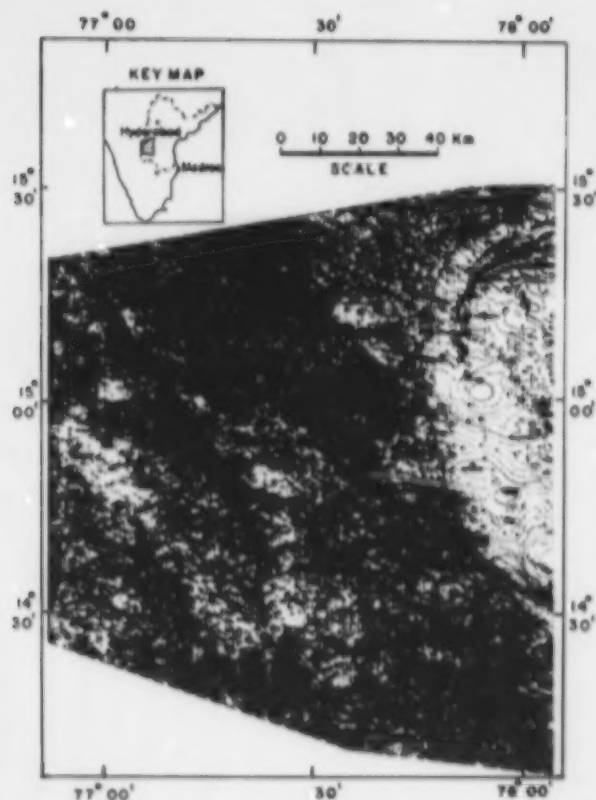


Figure 76.5. Aeromagnetic contour map of an area covering the Archean basement west of the Cuddapah Basin. The north-south flight lines, spaced 1 km apart except over the kimberlite belt, where lines were 1/2 km apart, were flown at a nominal ground clearance of 150 m. Contour interval is 20 gammas. The data is not corrected for the geomagnetic dipole field. There are many basic dikes in different orientations which traverse this area. The strong linears visible in this map were initially thought to be due to these dikes, but closer examination showed that these large scale linears are basically faults/fractures while some are due to dikes.

interval of 2 km. No kimberlite indicator could be found in any of these samples.

## STUDY OF GRAVEL HORIZONS AND MORPHOLOGICAL FEATURES

The absence of indicator mineral grains in stream gravels in an area in which diamonds are frequently found on the ground, led to a closer examination of the locations where diamonds had been found, and of the morphological features of the area.

The black soil layer of this region, at about 470 m elevation, had been already recognized as a major paleosurface. It was found that there are several localities in the southern part of the black soil area, and farther south in the granitic terrain, where



Figure 76.6. Ground magnetic map contoured at 50 gamma interval over a small part of the black soil area. Note prominent near east-west linear close to Pipes 1 and 6, and also a northwest linear, shown with open arrowheads. Almost nonmagnetic mylonitized granite was found along the near east-west linear under the soil.

gravel horizons were present on this surface. Between the present level of river Penner and this old surface, there were additional flats showing gravel. It was found that the reported occurrences of diamonds in the granitic terrain in the southern area coincided with the presence of gravels. In the project area also, the known locations of diamond find, which were in flat cultivated areas adjoining stream channels, coincided with areas of gravel. The observations led to the conclusion that most of the diamond finds in the area were related to gravel horizons which were not first generation deposits. If these diamond finds were not related to undisturbed



first cycle deposits, the clustering of such finds in an area did not necessarily imply the presence of the source kimberlites in the proximity of these clusters, as earlier assumed.

At present, the drainage in the project area is southward, into the Penner river, and northward into the river Krishna, with the water divide going east-west. It has been proposed that the river Penner was originally flowing northward (Vaidyanadhan 1965). This makes it likely that other northward-flowing tributaries to the Krishna might also have drained the region of kimberlite intrusions and created all the lower Krishna alluvial diamond deposits; some of these diamonds having been left behind in the project area. It was argued that the gravels in the project area, if reworked by southward drainage towards the present course of Penner, should leave some indications of such reworking having taken place.

Examination of satellite images of the area with particular attention to the distribution of alluvium (Chetty and Satyanarayana Rao 1986) showed that even first order streams in the region north of Penner, south of the east-west watershed, are associated with thick alluvium. Ground checks revealed the presence of mature gravels below these alluvial deposits. This evidence indicates that gravel deposits at levels such as 430 m at Nalladasarapalli ( $77^{\circ}25'30''\text{E}$ ,  $15^{\circ}05'30''\text{N}$ ) where diamond finds are common, are not first generation deposits. The presence of a mantle of iron oxide of about 2 mm in thickness on well rounded pebbles in such gravels at intermediate elevations, is additional evidence showing that these pebbles were derived from older, high-order river courses.

## DISCOVERY OF A KIMBERLITE

In the light of the above information it appeared necessary to make a shift southward from the originally selected area for examination. Moreover, there were doubts about the effectiveness of manual panning for concentrating the heavy minerals.

Fresh samples were collected from a number of tributaries of the Penner River from locations near their confluence with the Penner. These stream samples were passed through a Wilfley table and a high intensity magnetic separator. This was followed by gravity separation using tetrabromoethane. The heavy fraction was then sieved into different size components, and examined in reflected light under a binocular microscope.

Five of these samples showed one or two grains of kimberlite indicator minerals. Three of the samples seemed to be unrelated to any of the known kimberlites. These indications were then followed up by further sampling upstream.

The follow-up of one of these indications led, through increasing presence of indicators, 5.4 km

upstream, to a kimberlite under cover of red soil (Guptasarma *et al.* 1986). No outcrop of kimberlite was seen. The area is surrounded by low hillocks of amphibolite. A few granite boulders are also seen in the area. There was some calcrete on the surface, very similar to the frequently seen calcrete in the area, with the difference that it contained pseudomorphs of subrounded olivine grains, so characteristic of the kimberlite, as well as grains of all three types of indicator mineral. The kimberlite was struck in shallow pits in two locations where concentrations of such calcrete were found on the surface. This was the seventh kimberlite found in the area. Figure 76.7 shows its location. Its dike-like shape, found by trenching and drilling over a length of about 400 m, can be seen in Figure 76.8. The other indications led to some scattered occurrences of indicator minerals, but did not result in any more discovery.

This new kimberlite has undergone very uneven weathering. Drill cores could be collected at depths as shallow as 6 m in some places, but at other locations the weathering was seen to have proceeded to depths of about 15 m. The weathered rock is light yellow, and is very friable. Soaked in water it quickly disintegrates into a mud. The unweathered rock is bluish grey in colour. In a hand specimen it is highly

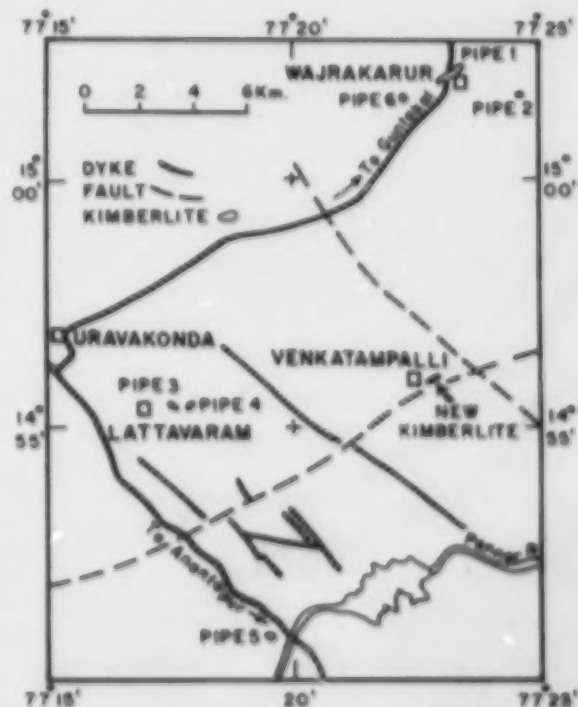


Figure 76.7. Location map showing the new kimberlite (after Gupta *et al.* 1986). Note displacement of dike by the east-northeast-trending fault.



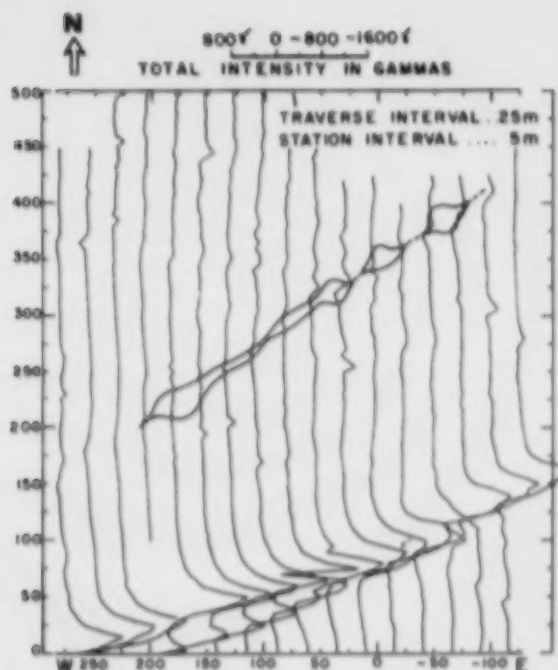


Figure 76.8. The new kimberlite, showing its northeast-trending pinch-and-swell structure, and a stack of ground magnetic profiles over it. The strong anomaly parallel to the kimberlite near the bottom of the diagram is due to a buried dolerite dike.

inequigranular rock with many rounded phenocrysts of altered olivine/serpentine, and frequent inclusions of rounded grains of pyrope garnet, picro-ilmenite, phlogopite, and some chrome diopside. The garnet grains frequently exhibit a kelyphitic cover and a typical pitted surface.

Microscopic examination showed that the primary constituent minerals are olivine, phlogopite, garnet, diopside, and opaque minerals; secondary minerals being serpentine, chlorite and calcite. Perovskite grains are distributed throughout the groundmass, of which monticellite constitutes about 2 percent.

Estimates of the pressure-temperature conditions of origin of the kimberlite were made by electron probe analysis of garnet and clinopyroxene grains. Analysis of Ca and Cr contents of garnets were also made. These studies showed that the kimberlite had a peridotitic environment of origin, and had come from a pressure-temperature regime within the stability field of diamond. Preliminary tests of a small quantity of the weathered kimberlite by the GSI resulted in the finding of one grain of a clear microdiamond weighing about 8 mg.

It is interesting that the dispersion halo of indicators in the soil above, and in the immediate vicinity of the kimberlite, has some correspondence with its shape. Study of the pattern of dispersion of indicators downstream from the kimberlite shows that the volume of ilmenite, as a fraction of the total volume of indicators, increases with increasing distance from the source before losing statistical significance (Table 76.1).

## GEOPHYSICAL MEASUREMENTS OVER THE NEW KIMBERLITE

The new kimberlite was covered by magnetic measurements, with a proton magnetometer, DC and telluric resistivity, EM and gamma ray spectrometric measurements taken mainly to find out if any of these methods could be used to locate other similar kimberlites in the area. Many trenches were also dug across the kimberlite in order to determine the shape of the kimberlite and also to examine the nature of the contact between the kimberlite and the country rock.

This kimberlite dike is parallel to an east-northeast-trending fault, and is within a distance of about 300 m from the fault. The fault runs for many kilometres, and is in line with one of the long aeromagnetic linears in the area. It is also clearly seen as a line in air photographs in which it can be traced over a length of about 15 km. There is a buried dolerite dike, with little surface expression, emplaced near the kimberlite along this fault.

The magnetic susceptibility of the fully weathered kimberlite was found to be very small, within  $20 \times 10^{-6}$  units. The susceptibility of the harder drill

TABLE 76.1. NATURE OF DISPERSION OF INDICATOR MINERALS DOWNSTREAM.

Distance (metre)	Pyrope garnet	Picro- ilmenite	Chrome diopside	%Garnet	%Ilmenite	%Chrome diopside
	(volume, arbitrary units)			(% of total vol. of indicators)		
30	28.3	7.1	2.3	75	19	7
100	40.5	20.8	0.8	65	33	1
1100	40.2	41.8	3.6	46	48	6
2200	2.9	9.2	0.1	24	73	1
2400	0.7	1.9	0.0	27	73	0
3400	0.1	0.0	0.0	100	0	0

core specimens was seen to be much higher, though variable, the largest measured value being  $2300 \times 10^{-6}$  cgs. It was quite surprising that the kimberlite did not have a strong magnetic expression throughout its length. Modeling showed that if the susceptibility of kimberlite below 15 m depth was at least  $2300 \times 10^{-6}$  units, and the kimberlite dike was assumed to extend vertically to great depths, there should have been a very strong ground magnetic anomaly over it. In fact, the dolerite in the fault near the kimberlite shows a very strong, systematic anomaly. Its magnetic susceptibility, measured from core samples, was seen to be about  $4800 \times 10^{-6}$  cgs. The absence of a magnetic anomaly over the kimberlite, as expected on the basis of the measured susceptibility, is perhaps an indication of low concentration of magnetite in the deeper parts of the kimberlite dike; somewhat higher local concentrations in the partly altered portions above; and very little magnetite in the fully weathered part just under the soil. Figure 76.8 shows magnetic traverses over the kimberlite and the dolerite.

DC resistivity and telluric current resistivity measurements failed to show any unambiguous anomaly that could be obviously related to the kimberlite. EM measurements with the GS-100, and gamma ray spectrometric measurements also failed to show any anomaly clearly attributable to the kimberlite.

The failure of electrical, magnetic, and radio-metric measurements to show obvious responses from this kimberlite is similar to the failure of these methods in finding a characteristic response from the other known kimberlites in the currently eroding area.

### POSSIBLE SIGNIFICANCE OF THE MAGNETIC LINEARS

Although the magnetic measurements did not show clear indications of kimberlite emplacement, it is possible that the magnetic linears have some significance in this context, particularly in providing indirect information useful for selecting areas for detailed search.

The fact that Pipes 1, 2, and 6 are practically on such an east-west linear, and that the new kimberlite dike is just parallel to, and very near an east-northeast linear, may be indicative of some kind of control on the localization of the kimberlites during the last part of their ascent. Information available so far does not allow any definite conclusion to be made. But there is evidence to show that many of the faults and dikes in this region are older than the time of emplacement of the kimberlites, which is of the order of 1 Ga.

There are a large number of basic dikes in the area. A detailed study of these dikes was undertaken in order to elicit all possible information regarding

the regional tectonic history of the area, particularly relating to the formation of the Cuddapah Basin, and the history of mafic and ultramafic igneous emplacements (Murty *et al.* 1985). K-Ar and Ar 39/40 dating was carried out for many of the dikes in addition to studying their chemical and petro-mineralogical nature. Their orientations and crosscutting relationships were studied in order to decipher the history of large stresses to which this part of the crust has been subjected in the Archean and early Proterozoic times. Palaeomagnetic measurements were also made on many of the dikes. These studies have shown that many of the dikes in this region were emplaced as long ago as 2.2 Ga. The pattern of dikes and faults, in relation to the Proterozoic Cuddapah Basin, indicates a number of epochs of emplacement of dikes, and also a number of periods of faulting on a crustal scale, creating many intersecting linears oriented east-northeast, east-west, east-southeast and southeast. The east-northeast linear near the new kimberlite has displaced older north-northwest-trending dikes by about 500 m (Figure 76.7). The near east-west linear near Pipes 1, 2, and 6 also shows shear deformation in the form of mylonitization. It is possible, that of the various magnetic linears in the area, those which relate to shear movements are relevant from the point of view of possible kimberlite emplacements. At least the emplacement of the new kimberlite may have been controlled by an east-northeast-trending linear weak zone.

### DISPERSION OF INDICATOR MINERALS

The most important contribution to the successful detection of the new kimberlite was provided by the stream sediment sampling activity. As such, the occurrence and the manner of dispersion of the indicators from the eroding kimberlites is quite important for the purpose of exploration. The characteristics of this dispersion process may be summarized as follows:

1. The incidence of indicator minerals is different in different kimberlites. But pyrope garnet, picro-ilmenite, and chrome diopside are present in small quantities in most of them. Detection of new kimberlites using heavy mineral sampling would need careful choice of the location, level, and nature of material for sampling, and effective concentration of heavies with the help of mechanical devices like Wilfley table, high intensity magnetic separator, and so on.
2. The most important indicator mineral is pyrope garnet. The colour of garnets seen in these kimberlites varies over a wide range, but the ones which can be most easily spotted under the microscope are the lilac-coloured ones. They are characterized by conchoidal fracturing, absence of inclusions and, when near the source, presence of a pitted surface, or remains of a kelyphitic cover. The picro-ilmenites are more diffi-

cult to visually distinguish from other dark minerals, particularly chromite. The ilmenites break under applied pressure into many tiny conchoidally fractured fragments which have very highly polished surfaces. Naturally broken ilmenites, however, show dull outer surfaces. Very near the source one can expect to find some micro-ilmenites having a liquid drop-lustre.

3. The ilmenites are expected to travel farthest, being detectable up to distances of about 4 km, or more, from the source. Garnets travel somewhat less, and chrome diopsides may not be detectable beyond 2 km. Of the three indicators the volume fraction of garnets, out of the total volume of indicators, is largest near the source. The corresponding volume fraction of micro-ilmenite seems to increase with distance from the source before getting lost in statistical noise at large distances.
4. The streams in the northern part of the study area, around the east-west watershed separating the tributaries to river Krishna from those to the Penner, are very weak seasonal streams which may not be creating gravel adequately representative of the eroding bedrock. Rather than concentrating the heavy minerals in their beds, these streams may actually be dispersing them.
5. There has been some dispersion of indicators in the soil-covered area as well. Indicators have been found downstream of Pipe 6. There are also some isolated occurrences of indicators in stream beds in the black soil area. Some of these may have been left by older streams and it may not be possible to connect them with their original sources.
6. In the area close to the western margin of the Cuddapah Basin there are streams which are draining the basal conglomerates of the Kurnool Formations. Since these conglomerates contain kimberlite indicators which are now being dispersed, stream sampling in this area may lead to these conglomerates instead of kimberlites.
7. Recent changes in the course of streams in the currently eroding area have also left behind isolated concentrations of indicators in the soil. Examination of air photographs was found to be helpful in identifying such older courses. Interpretation of the incidence of indicators in loam samples must be done by taking such changes into account.

The above characteristics of the dispersion can provide useful guidelines for exploration of new kimberlites in this region.

## CONCLUSIONS

The application of an integrated approach using geological, geochemical, and geophysical information

has been found to be successful for kimberlite exploration in the Wajrakarur area of Andhra Pradesh, India.

Satellite images and air photographs provided information about features like faults, large scale lineaments, and geological as well as morphological data. Aeromagnetism provided evidences relating to crustal faulting as well as indirect information regarding the possible stress regimes in the Archean period. Geochemical and geochronological studies of basic intrusions in the area showed that there have been epochs of large scale dike emplacement prior to the emplacement of kimberlites. All these were important in localizing the area for ground search activity. A similar integrated approach should prove to be useful for further exploration in this region.

Two distinct methods need to be applied for ground exploration in this region. For the soil-covered portions, time domain EM surveys should be most effective in locating and delineating those kimberlites which have undergone deep weathering. To a certain extent, soil sampling for heavy minerals should also be useful, particularly for examining samples from the EM anomaly zones for the presence of indicator minerals.

For the currently eroding area, the best approach would be to use stream sediment sampling for pyrope garnet, micro-ilmenite, and chrome diopside as principal tracer minerals. This should be supplemented by loam sampling, controlled by air photo studies aimed at taking into account recent changes in the stream courses, if any.

Because of the variability of physical properties and of the degree of weathering suffered by the kimberlites, ground geophysical methods are unlikely to succeed in the currently eroding area.

The occurrence of calcrete with pseudomorphs or kimberlitic olivine can be a very important guide to the presence of kimberlite in the immediate neighbourhood.

## ACKNOWLEDGMENTS

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# 77. The Faille B Gold Deposit, Northern Haiti: An Exploration Case History

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## ABSTRACT

The Faille B gold prospect represents a potentially significant area discovered by the United Nations Revolving Fund for Natural Resources Exploration (UNRFNRE) and is located in the Grand Bassin exploration zone, 37 km east-southeast of Cap-Haitien in northern Haiti. The prospect was discovered by the combination of soil geochemical surveys and detailed geological and structural mapping, and was further tested by IP, resistivity, magnetic surveys, and extensive trenching and pitting work. Further evaluation over a strike length of 1.8 km comprised of 31 diamond-drill holes totaling 3185 m.

In the regional context, the Faille B prospect is located within a northwest-southeast-trending tectonic zone which represents a trace of the major Hispanola fault, characterized by shear zones, steeply dipping sheets of ophiolites, and of tonalite intrusions. Metallogenically, the prospect is part of a mineral district defined by widespread porphyry and vein copper mineralization.

Gold mineralization occurs in the form of quartz veins and irregular lensoid bodies associated with tonalitic intrusions into ophiolites and eugeosynclinal marine sediments, in an oceanic and continental margin setting. The overall characteristics of the mineralization are similar to the genetic types known from the mineral districts of California, particularly of Grass Valley. Gold values in the veins range up to 226 g/t over a 1 m interval, and the estimated probable reserves within a small portion of the 4.5 km long auriferous structure are 0.5 million tonnes at 14.1 g/t Au.

The exploration history leading to the discovery and present knowledge of the deposit will be described.

## INTRODUCTION

### GENERAL

This presentation is a progress report on the exploration of the Faille B gold deposit in Haiti, discovered and explored by the United Nations Revolving Fund for Natural Resources Exploration between 1983 and 1987.

Haiti has no history of gold mining. The only two significant metalliferous mines were the Reynolds bauxite mine in the Miragoane district of

the Jacmel Peninsula in the south, and the Sedren Meme copper mine in the northwestern part of the country near Gonaives, which operated for a short time in the late 1950s.

It is interesting to note that the first European settlement in the New World was established at La Navidad near the present Fort Liberté following the shipwreck of Columbus' flagship Santa Maria (Figure 77.1). Legend has it that the native Arawak Indians were festooned in gold jewelry. One of Columbus' captains volunteered to stay behind, while the remaining two ships returned to Spain with the news of the gold discovery to seek reinforcements. The second fleet found the stockade burned to the ground and the garrison massacred. This site has recently been discovered and is being excavated. The coast at the time appears to have been some distance south of the present shoreline, putting the site of the settlement very close to the Faille B gold prospect. The Indian gold must have been derived from panning in the creeks, and even today there is an unknown amount of gold artisanally collected by the natives during the quiet time in the agricultural calendar throughout northeastern Haiti.

## LOCATION

Faille B lies within Zone A, known as the Grand Bassin area, one of six zones investigated under a

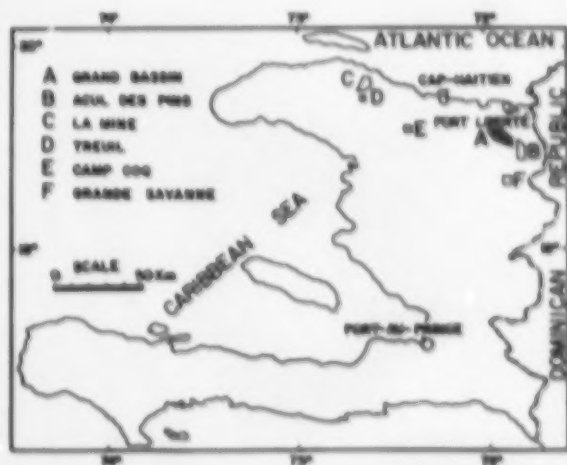


Figure 77.1. Location map of the Fund's exploration zones in northern Haiti.

Project Agreement between the Revolving Fund and the Government of Haiti. Zone A, originally covering 73 km², later reduced to 50 km², is situated about 35 km east-southeast of Cap-Haitien, the second largest city in the country.

The topography around Faïlle B consists of gently rolling open country, with northwest-southeast-trending hills rising to 210 m above sea level.

#### REGIONAL GEOLOGIC SETTING

Haiti, the western half of Hispaniola, represents a segment of the Greater Antilles Cretaceous - Early Tertiary calc-alkalic volcanic arc, formed at the convergent plate margins of North America and the Caribbean (Bowin 1975; Kesler 1978) (Figure 77.2). The geological framework of Northern Haiti is dominated by the Massif du Nord, the northwest- to east extension of the Cordillera Central of the Dominican Republic, the "backbone" of Hispaniola, and formed mainly of pre-Albian rocks and Upper Cretaceous - Lower Tertiary plutonics.

The Faïlle B prospect is located in the northeastern part of the Massif du Nord. It is approximately 200 km west-northwest of the Pueblo Viejo mine in the Dominican Republic, currently one of the largest gold producers in the Western Hemisphere.

The oldest known rocks in the Massif du Nord in Haiti are the Jurassic Morne Cabrit Series of ophiolites, thought to be equivalent to the Duarte Formation in the Dominican Republic (Figure 77.3).

This ophiolitic suite is overlain by the Lower Cretaceous Perches Series, consisting mainly of carbonaceous shales and acid volcanoclastics, most likely the equivalent of the Los Ranchos Formation, a member of which is the host for the Pueblo Viejo gold mine in the Dominican Republic.

Upper Cretaceous volcanism in the Massif du Nord consisted of early basalts and andesites evolving to younger dacites. Volcanic activity was interspersed with sedimentation and a thick volcano-sedimentary pile was constructed. The andesitic member of this volcanic pile is known as the Terrier Rouge Series and the acid member as the La Mine Series.

The Upper Cretaceous - Paleocene interval was marked by batholithic tonalitic plutonism and high-level acid intrusives, some with associated porphyry copper mineralization.

The most prominent structural feature in the Massif du Nord is the northwest-southeast pattern of synclines and anticlines with sympathetic alignment of major fault zones. The synclines are generally filled with volcano-sedimentary rocks, whereas the eroded crests of the anticlines are almost exclusively occupied by the batholith.

Zone A itself is dominated by the Perches Syncline and major complex northwest-southeast-trending faults (Figure 77.3).

#### PREVIOUS EXPLORATION WORK

Between 1972 and 1978, regional geologic mapping, metallogenic studies, and geochemical exploration were carried out in northern Haiti by three successive United Nations projects, jointly with the Haitian Department of Mines and Energy Resources (DMRE).

The area was also mapped by Philippe Nicolini (1977) for his Ph.D. thesis.

Several broad Cu-Zn anomalies were discovered by stream sediment surveying in the Département du Nord-Est. One of these is located in the Grand Bassin area and covers an area of about 50 km². This anomaly is characterized by values

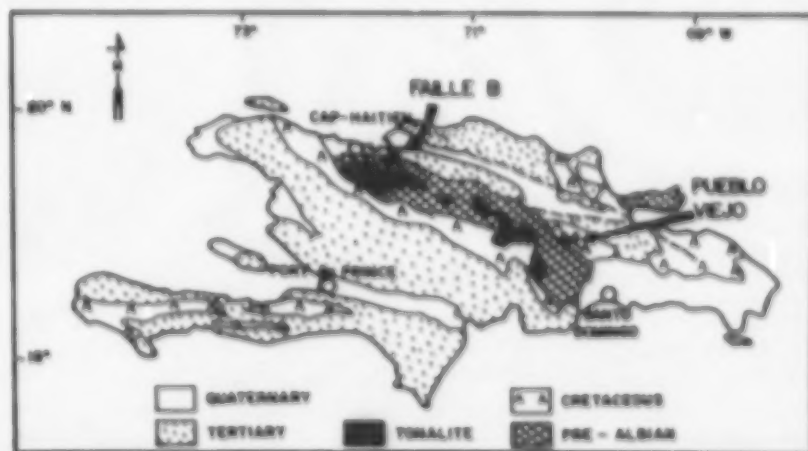


Figure 77.2. Simplified geological map of Hispaniola.

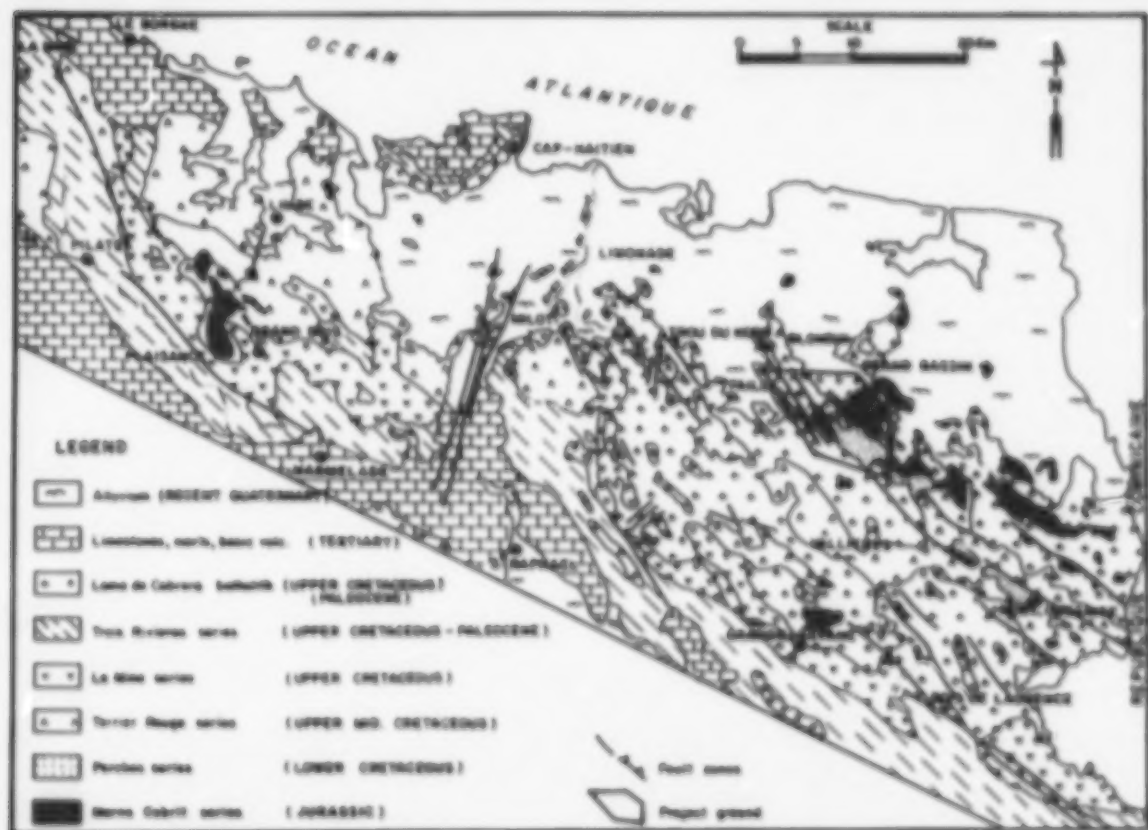


Figure 77.3. Geological map of northeastern Haiti.

ranging from 200 to 1300 ppm Cu and from 75 to 140 ppm Zn (Figure 77.4).

Follow-up soil surveys in the northern part of this anomalous zone outlined several anomalies ranging over 1000 ppm Cu and drilling of these resulted in the discovery of two large low-grade porphyry copper deposits.

At Douvray, the resource has been estimated at 200 million tonnes of 0.6 percent Cu, while at Blondin the resource is in the order of 100 million tonnes with average grades of about 0.5 percent Cu.

Douvray is situated only 2.5 km north and Blondin 5 km north-northwest of the Faille B prospect, which was not known at that time. The average Au content of the mineralization at Douvray is in the order of 0.2 ppm, but the best drillhole intersection at Blondin was 5.9 g/t Au over 1 m.

Several small isolated anomalies ranging up to 1000 ppm Zn were located by these soil surveys. Although many of these coincide with Cu anomalies, some are independent, without any obvious relation-

ship to porphyry copper mineralization. Background Au contents of soils were found to be in the order of 0.01 to 0.05 ppm, with higher background values associated with carbonaceous shales of the Perches Series and with the Morne Cabrit ophiolites.

The coexistence of Zn and Au soil anomalies at both Grand Bassin and Pueblo Viejo, and the apparently similar age and stratigraphy of parts of the Perches Series and the Los Ranchos Formation, as well as the presence of intense iron staining and oxidation in some parts of the Perches Series, led the Fund to the concept that the carbonaceous shales might constitute targets for gold-silver mineralization of the Pueblo Viejo type.

Other isolated grab samples collected by Pierre Nicolini towards the end of the third UN project in 1978, from oxidized and silicified outcrops in the Faille area, showed up to 15 ppm Au. Panning of stream sediments also revealed several Au anomalies in the Grand Bassin area. There was insufficient time to follow up on these findings before that project ended.

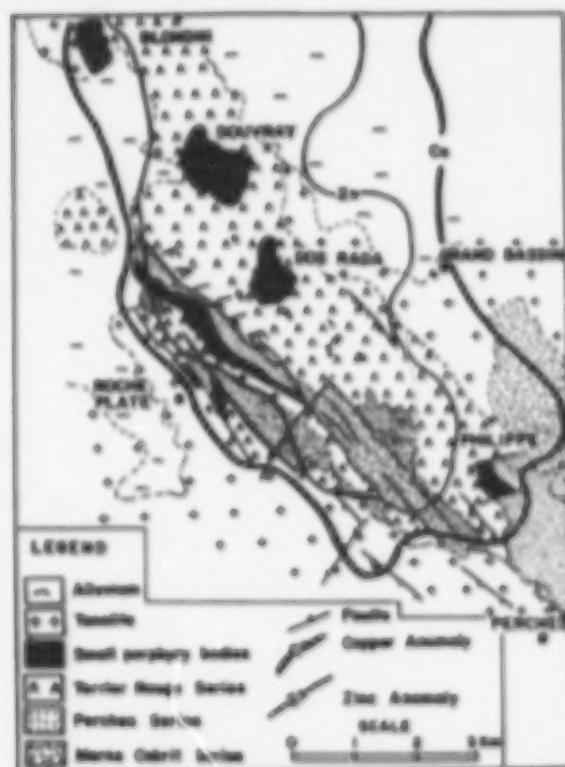


Figure 77.4. Geological map and stream sediment anomalies in the Grand Bassin area.

## PROJECT OBJECTIVES

Based on the above information and the steady rise in the price of gold, the Fund selected and defined Zone A in order to explore for the following:

1. the Pueblo Viejo type of gold-silver mineralization
2. stockwork porphyry gold deposits of the Porgera, Hauraki, and Cinola type
3. the source of the anomalous gold outcrop samples and pan concentrates in the general Faïlle area

## EXPLORATION SEQUENCE

Fourteen target areas for the Pueblo Viejo and stockwork porphyry models were selected and followed up in 1983 by geological mapping, soil and rock sampling, and trenching. This work was completed within a reasonably short time (Figure 77.5).

The Perches Series, particularly the sedimentary units containing black shales, was thoroughly checked and sampled. Except in the Faïlle area, no significant mineralization was found. The black shales were generally restricted to patchy isolated outcrops, not comparable with the extensive and thick Pueblo Viejo member of the Los Ranchos Formation in the Dominican Republic.

Potential targets for stockwork gold mineralization were selected on the basis of pre-existing geochemical data and distribution of mineralized porphyry stocks. Targets were checked by systematic rock sampling, but no particularly encouraging results were obtained.

## LEGEND

Areas Followed-Up by UNRPMRE

- |                               |                        |
|-------------------------------|------------------------|
| ① Perches                     | ⑩ Perches              |
| ② Marine Carbonate            | ⑪ Porphyry de Philippe |
| ③ Faïlle A                    | ⑫ Chénoué              |
| ④ Faïlle B                    | ⑬ Marine de l'Or       |
| ⑤ Marine Carbonate Au-ville   |                        |
| ⑥ Marine Carbonate South East |                        |
| ⑦ Zinc Anomaly                |                        |
| ⑧ West Chénoué                |                        |
| ⑨ Chénoué                     |                        |
| ⑭ La Croye                    |                        |

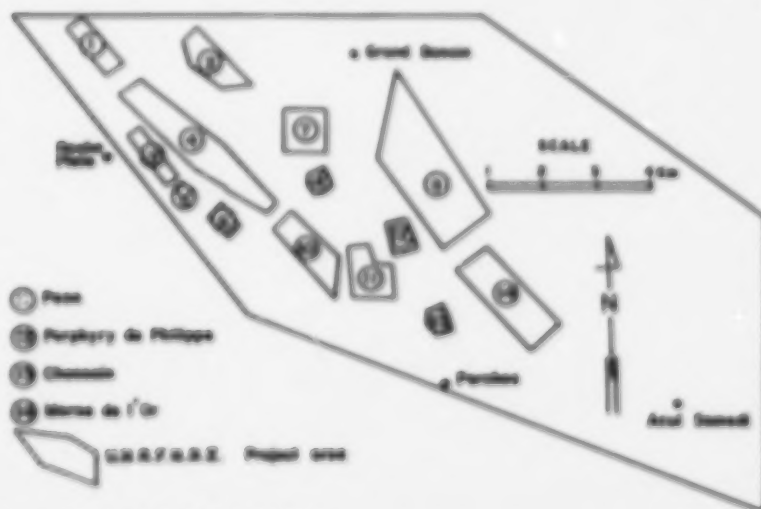


Figure 77.5. Location map of target areas in the Grand Bassin area.



During reconnaissance of the Morne Cabrit-Fraiche-Faille target areas, quartz veining was noted over a strike length of 1 km, but assays of a few grab samples gave little encouragement.

Within this subgroup of target areas, attention was first focused on the Faille A area, where a soil grid revealed base-metal anomalies without Au or Ag.

Attention then turned to Faille B, initially near the base-metal anomalies in the Perches Series. A few lines of soil samples were analyzed for Au and anomalous values ranging up to 3 ppm obtained in November 1983. Trenches were cut on these and the second trench, FB2, cut a network of quartz veins, now called the Alpha Shoot, which averaged 45 g/t Au over 3 m (Figure 77.6). For the next nine months, exploration concentrated on this showing, at first thought to be genetically related to the bed-

ded auriferous barite discovered about the same time in the Perches Series. Due to significant exploration activities in two other Project Zones, however, it was not until September 1984 that routine soil sampling for Au was continued out south of trench FB2. Trenching on new Au soil anomalies led to additional discoveries and the significance of the Main Zone system of auriferous quartz veins was recognized, and its relationship with the micro-tonalite understood.

Detailed exploration work at Faille B, including gridding, geophysics, trenching, and drilling, was then carried out over the entire 1.8 km length of the mineralized zone.

Towards the end of the Project, exploration efforts were concentrated in the Central Zone, where geochemical and drilling results indicated the presence of more intense gold mineralization. An attempt was made to identify potential underground mining reserves in this area by drilling and testing the lateral and vertical continuity of the individual quartz veins and gold values. Problems encountered included the erratic distribution of gold and the low recovery and broken core in quartz veins. In order to establish confidence levels which could be used in reserve calculations, several veins were exposed by manual stripping over a small area of the Central Zone and sampled.

As an alternative, the potential bulk open-pit mining reserves of the Central Zone were also studied.

## PROJECT ACTIVITIES AND METHODOLOGY

The overall Faille area was mapped at 1:10 000 and the Faille B prospect was gridded and mapped at 1:2000. Detailed maps from scales 1:200 to 1:1000 were prepared for individual trenches or quartz vein systems. The 1:2000 geological map of Faille B formed the basis for all geochemical work, while cross-sections guided the drilling. Lithological boundaries and faults were accurately established by trenching and contacts were in most cases encountered in drillholes at anticipated depths. Geological mapping and rock descriptions were supported by study of thin sections of various representative rock types.

A total of 760 soil samples were collected on the Faille B grid, all being analyzed for Au and Ag, and a large number additionally for Cu, Pb, and Zn. Samples were collected at 25 m intervals along lines 50 m apart and in several cases at 25 m spacing for better definition of the anomalies. Soil samples were generally collected from a depth of 15 to 20 cm. The samples were not sieved, but were directly crushed and pulverized to minus 120-mesh for analysis.

Resulting Au anomalies were tested by 68 manually excavated trenches totaling 2.4 km in length

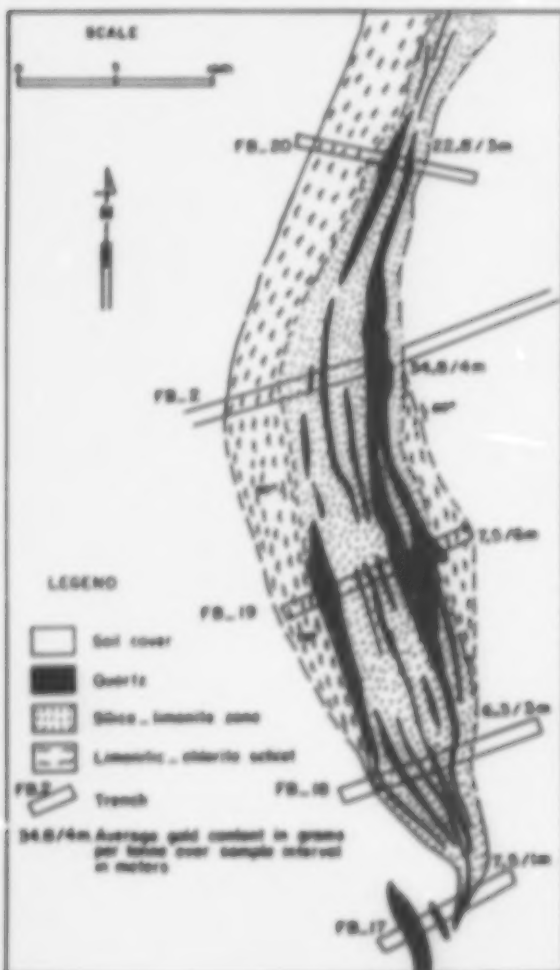


Figure 77.6. Plan of auriferous sheeted quartz vein in the Alpha Shoot.

and by 27 shallow pits. In several cases, trenches were designed to trace the lateral continuity of the auriferous quartz veins, while in the Central Zone the multiple quartz vein system was later stripped, with both walls of the quartz veins being exposed along their strike. The length of the individual trenches ranged from a few metres to 120 m, and their depth between 1 and 3 m. Representativity was checked by resampling the quartz veins, while the distribution of gold was tested by sampling the veins along their strike extent. A total of 1730 channel samples and continuous composite chip samples were collected from trenches.

Geophysical work consisted of IP (Time Domain and Phase)/Resistivity and Proton Magnetometer surveys for a total of 17.5 line km and 13.1 line km, respectively. A dipole-dipole array was used in the Phase IP/Resistivity surveys at 25 m spreads, with detailing at 5 m, 10 m, and 40 m spreads. The objectives of this work were to search for additional vein systems not detected by the geochemistry and trenching, and to provide supplementary information on the overall structural setting of the mineralized zone.

Drilling at Faille B, which began in September 1985, involved 31 diamond-drill holes totaling 3185.65 m. Drillhole depths ranged from 44 to 190 m, and apart from two subvertical holes, all others were inclined between  $-54^{\circ}$  to  $-60^{\circ}$ . NQ core was retrieved as deep as possible before converting

to BQ wire line. The average core recovery was about 83 percent, but was lower in quartzose vein material.

The initial 19 exploratory holes were sited over a strike distance of 1.8 km at spacings which ranged from 120 to 250 m. Subsequent holes consisted of infill drilling and drilling across sections to check lateral and vertical continuity of the auriferous quartz veins to increase the confidence level of reserve estimates in the Central Zone of Faille B between Lines 100N and 200S.

Core sampling intervals in the mineralized zones varied from 0.5 to 1 m, and in the visually unmineralized sections up to 2 m. After splitting into two by sawing, the first half of the core was ground to minus 20-mesh and split again. Half was then ground to minus 120-mesh, resplit, and half used for assay and for reference. In order to avoid bias in completely broken core with very low recovery, the entire sample was ground to minus 20-mesh. Checks on the oversize and on the second half of the core indicated small, acceptable variations in the Au values. Analytical results on sludge from one drillhole were not sufficiently reliable to recommend such sampling for a routine practice.

Apart from a small number of core and trench samples analyzed by fire-assay, the remainder were analyzed by atomic absorption spectrometry following an aqua regia attack and MIBK extraction for Au and  $\text{HClO}_4\text{-HNO}_3\text{-HF}$  attack for the other ele-

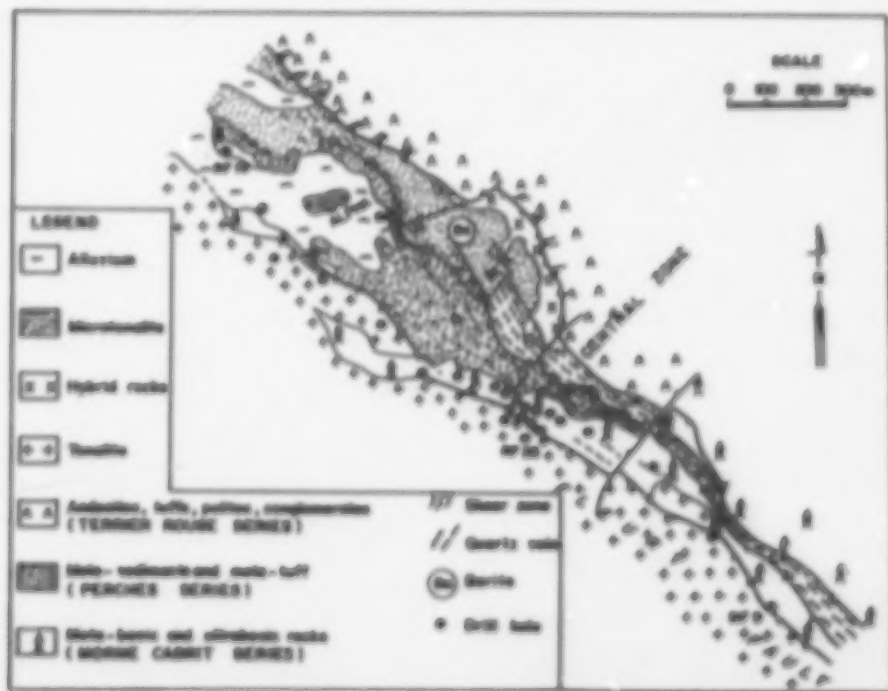


Figure 77.7. Geological map of Faille B prospect.

ments at the DMRE laboratory in Port-au-Prince. Control samples and subsamples were systematically analyzed and results both from internal and external laboratories showed good reproducibility of gold values in subsamples and acceptable accuracy and precision in control samples.

## EXPLORATION RESULTS ON THE FAILLE B PROSPECT

### GEOLOGY AND STRUCTURE

The Faille B prospect occupies the eastern part of a major tectonic zone, marked by a series of north-west-southeast faults which bring various litho-stratigraphic units into juxtaposition as tectonic sheets aligned parallel to the regional trend (Figure 77.7). The prospect itself is dominated from east to west by three subparallel northwest-southeast faults: the Eastern Fault, the Western Fault, and the Fleury Fault. All three faults have westerly dips varying between 30° and 70° and locally display curvatures along strike and depth.

The Eastern Fault is reverse and converges at depth and towards the south with the Western Fault (Figure 77.8). The narrow belt of country between the two Faille faults is characterized by destructive deformation and forms a major shear zone in the metabasites in the southern part of the prospect.

A series of northeast-southwest transverse faults divide the Faille B structure into blocks characterized by different angles of rotation and tilting.

Figure 77.9 is an isometric projection of the mineralized block viewed from the south.

The Morne Cabrit ophiolites consist mainly of peridotites, pyroxenites, hornblendites, metagabbros, and metabasalts. A spectrum of metamorphic grades up to the epidote-amphibolite facies is observed within the series. Tremolite-chlorite schists, actinolite-chlorite schists, and talc schists occur within highly tectonized shear zones. These metamorphosed rocks were mapped collectively as "metabasites".

The Morne Cabrit Series is stratigraphically followed by the Lower Cretaceous Perches Series, but in the prospect area, the latter occurs in the form of a discrete sliver, squeezed between the Eastern and the Western fault, and is represented by sheared and mylonitized metasediments, originally thought to be tuffaceous mudstones and cherty tuffites.

The Post-Albian Terrier Rouge Series occupies the northeastern part of the prospect and occurs on the footwall side of the Eastern Fault, in juxtaposition with all other formations. It consists of andesites, andesitic tuffs, conglomerates, agglomerates, and red hematitic mudstones. The conglomerates represent both marine and subaerial facies, and the

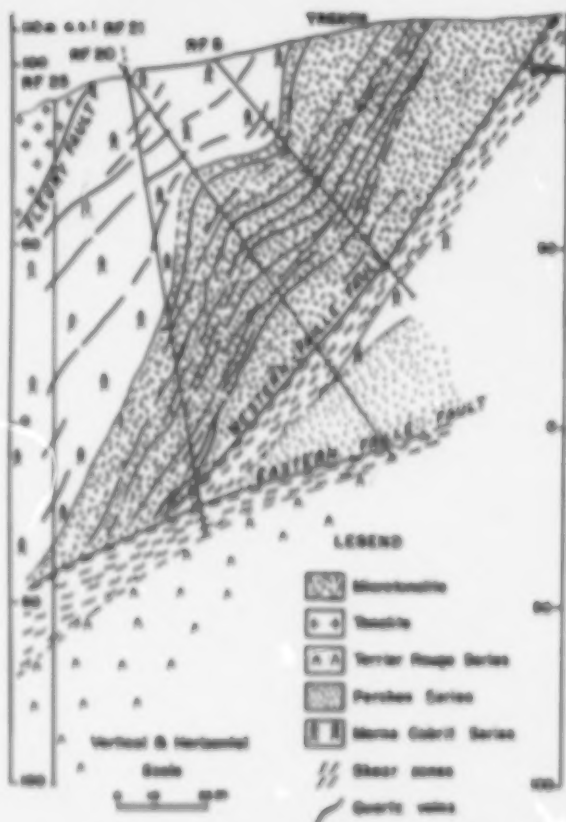


Figure 77.8. Drillhole cross-section in the Central Zone of Faille B.

andesites consist of massive flows which vary in composition and texture between various outcrops.

The Loma de Cabrera batholith is represented by an elongate northwest-southeast-trending body of coarse-grained hornblende tonalite, varying in width from 100 to 300 m. Towards the south, beyond the limits of the Faille B prospect, the intrusive connects with the major batholith. The body intrudes the metabasites and its eastern contact is marked by later faulting along the Fleury Fault which dips 65° southwest. It is generally quite inhomogeneous, containing high amounts of quartz-epidote stringers and partially assimilated xenoliths.

A microtonalite intrusive, the principal host of most of the auriferous quartz veins, is emplaced mainly in the metabasites, but also in the Perches Series, and partly in the main shear zone. The intrusive is a tabular, wedge-like body, faulted off at relatively shallow depths (<200 m) in the northern and central part of the grid. The microtonalite has a relatively fine-grained porphyritic texture, but is locally quite heterogeneous, with variations in texture, grain size, and modal composition. It is generally charac-

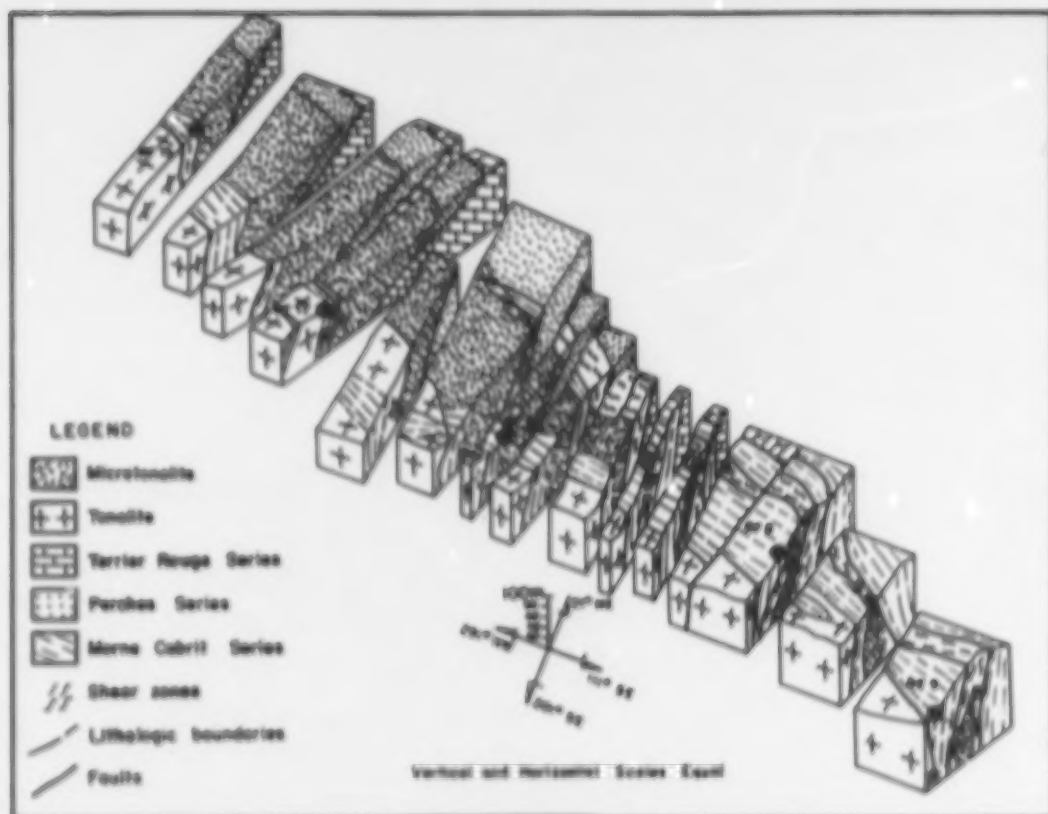


Figure 77.9. Isometric projection of Faille B prospect.

terized by strong chloritization with moderate propylitic alteration, and contains tiny stringers and impregnations of pyrite and chalcopyrite.

Although the relationship between the microtonalite stock and the batholith is not obvious within the mapped area, the former is interpreted as a late, high level phase of the latter.

## MINERALIZATION

### Stratabound Gold-Silver-Barite

Thinly laminated barite seams, varying in thickness from a few centimetres to 2 m, occur in the Perches Series (Figure 77.7). The laminations result from fine hematite, graphite, and tiny interlayers of chert and carbonates. The barite contains up to 5 g/t Au, 41 g/t Ag, 0.28 percent Pb, and 0.16 percent Zn. Jasperoid-like beds and lenses of recrystallized chert occur at various horizons and some appear to lie stratigraphically along strike of the bedded barite, representing its lateral facies. Fine-grained pyrite with delicate layering occurs as thin interlayers in the metatuffs and is generally associated with pervasive argillic alteration. The possibility of an affinity with

the Carlin model was initially considered but later rejected.

### Auriferous Quartz-Sulphide Veins

With the exception of the auriferous barite occurrences mentioned above, gold mineralization so far encountered at Faille B is restricted to quartz-sulphide veins. The Main Zone trends northwest-southeast along the axis of the microtonalite intrusive and so far two small, but rich shoots, Alpha and Beta, have been located. These strike almost north-south.

These generally cut the microtonalite stock and its wall rocks, particularly the metabasites, but also occur to a lesser extent in the major shear to the southeast. Veins in metabasites at surface have been found to cut the microtonalite at depth in some cases. The veins range from simple to exceedingly complex systems, such as multiple lenticular veinlets, sheeted banded veins, and sheeted systems of quartz veinlets. Most of the veins strike northwest-southeast, conformably with the structural grain of the area and have westerly dips ranging from 40° to 65°. Steeper veins with opposite dips, however, also occur, and in some cases vein material passes with



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Photo 77.2. Photomicrograph of core.

rite generally increases sympathetically with gold grades, but the reverse is not always true, at least according to the assays, although this effect may be due to the spotty distribution of the gold particles.

Gold contents in quartz veins from trenches range from traces to 230 g/t. Gold values persist with depth and only in a few cases was secondary enrichment of gold suggested in the oxidized zone, which varies from 15 to 25 m. High gold values such as 21 g/t, 60 g/t, and 200 g/t were encountered at depths between 35 and 120 m in the primary zone.

Positive and erratic gold mineralization was encountered by drilling and trenching over a strike length of 1.8 km, but the drill spacing does not allow any reliable reserve estimates for the entire mineralized area at this stage.

Calculations, however, were made for the Central Sector between holes RF11 and RF7, where the Main Zone quartz vein system is more strongly developed. It represents a small area 300 by 50 m, tested by 13 diamond-drill holes and 9 long trenches, in addition to several excavations along strike of the quartz veins.

Taking an average aggregate width of 4.7 m for the quartz vein material and a depth extent of 150 m, the auriferous material in this sector is estimated at 520 000 tonnes of 14 g/t Au. Estimates based on mineable underground widths are still being calculated.

The mineable open-pit resource to a depth of 50 m is estimated at 1.1 million tonnes of 2.4 g/t material.

Possibilities for additional resources exist in the southern part of Faïlle B, where drillhole RF9 on Line 900S encountered 5 g/t Au over a width of almost 3 m in a quartz vein.

The two rich shoots, Alpha and Beta, contain small reserves of readily mineable material.

The Alpha shoot, first discovered in Trench FB2 and the possible origin of Nicolini's 15 g/t Au sample, is a rich sheeted quartz vein which has been exposed over a strike length of about 50 m. It averages 3.4 m in width and grades 17 g/t Au. Drilling indicates that the shoot is faulted off at approximately 20 m depth (Figure 77.6).

The Beta shoot, first discovered in Trench FB41, is a sheeted quartz vein averaging 34 g/t Au over a width of 2.5 m. It is exposed over a distance of 50 m and was encountered by drilling at a depth of 60 m (Figure 77.11).

#### GEOCHEMISTRY

The auriferous quartz vein mineralization shows enrichment of Ag, Cu, and Te. The following elements appear to be somewhat enhanced: As, Sb, and F. Virtually all high-grade (>5 g/t) Au intersections in quartz veins carry anomalous Ag values which range from 3 to 18 ppm, with Au:Ag ratios averaging approximately 1.8:1, but in several cases high Ag values, up to 15 ppm, are not accompanied by economic Au contents, possibly due to the more spotty distribution of the latter.

Lithochemical results on rock samples and drill core show that metabasites and the Perches Series can be chemically distinguished from the other formations by their high Ni contents which range up to 1600 ppm. The hydrothermally unaltered Perches Series can be also distinguished from the other units by high Zn, Pb, and Ag contents which range up to 4 percent, 700 ppm, and 7 ppm, respectively. Within the hydrothermally altered and sheared members of this series, Ni decreases to 360 ppm, Zn to 50 ppm, and Pb to 25 ppm.

Direct analysis for Au in soils proved to be the most effective exploration technique in the discovery and follow-up of the Faïlle B gold mineralization. Background Au contents in soils are in the order of 0.05 ppm, while anomalous values range up to 34 ppm, with values of 0.3 ppm Au and higher generally indicative of mineralization (Figure 77.12). Cu is a better pathfinder for Au than Zn or Pb. Anomalous Cu values between 400 ppm and

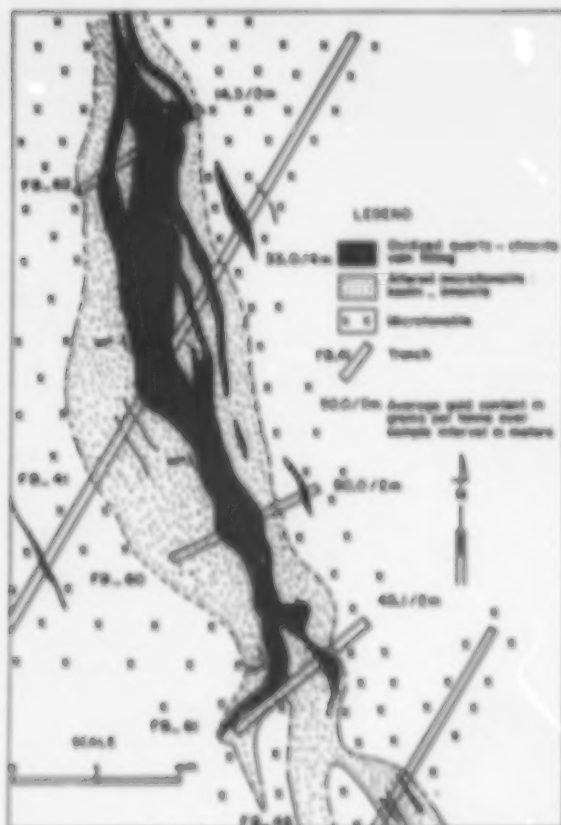


Figure 77.11. Plan of the auriferous quartz vein in Beta Sheet.

2500 ppm reflect the quartz-sulphide mineralization within the microtonalite and the metabasites.

Background ranges for Zn and Pb in soils were 50 to 100 ppm and 10 to 20 ppm, respectively. Both elements show distinct populations corresponding to the two types of gold mineralization. The most prominent overlapping geochemical patterns are characterized by 500 to 1100 ppm Zn and 100 to 1100 ppm Pb, which correlate excellently with the sedimentary barite mineralization in the Perches Series. A second pattern is less pronounced and correlates with the quartz vein mineralization in the sheared metabasites.

#### GEOPHYSICS

Phase IP and Resistivity surveys generally provided only supplementary information to the geological and geochemical results at Faille B. Drillhole RF9, however, was cited to test a strong IP anomaly and encountered 5 g/t Au between 127 and 130 m associated with strong sulphidation.

The IP results generally indicate broad and moderate magnitude anomalies which correlate well

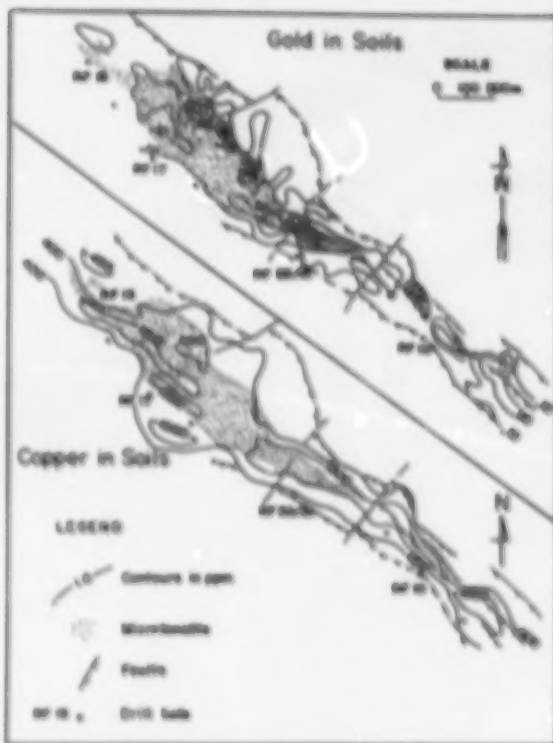


Figure 77.12. Gold and copper in soils at Faille B.

with the uniform pyritic mineralization within the microtonalite and surrounding wall rocks (Figure 77.13). Narrow IP anomalies are due to sulphide concentrations and fault zones.

The background of the total magnetic field in the area was taken as 41850 gammas. Above this, values generally ranged from 600 to 1400 gammas, with some localized high readings up to 3100 gammas over more massive unaltered ultramafic rocks. The magnetic profiles often indicated sharp narrow peaks in the vicinity of major faults.

#### DISCUSSION

In a regional context, the Faille B prospect is located within a tectonic zone representing a trace of the major Hispaniola fault or subduction zone characterized by the early injection of ophiolites and emplacement of linear tonalitic intrusives during one of the later phases of its reactivation.

A northwest-southeast-trending megafault can be traced from Faille B southeastward towards the Dominican Republic and northeastward to the Blindin porphyry copper deposit. This megafault also correlates with the distribution of alluvial gold occurrences in northern Haiti, making the prospect of further bedrock discoveries of similar type along this zone very favourable.

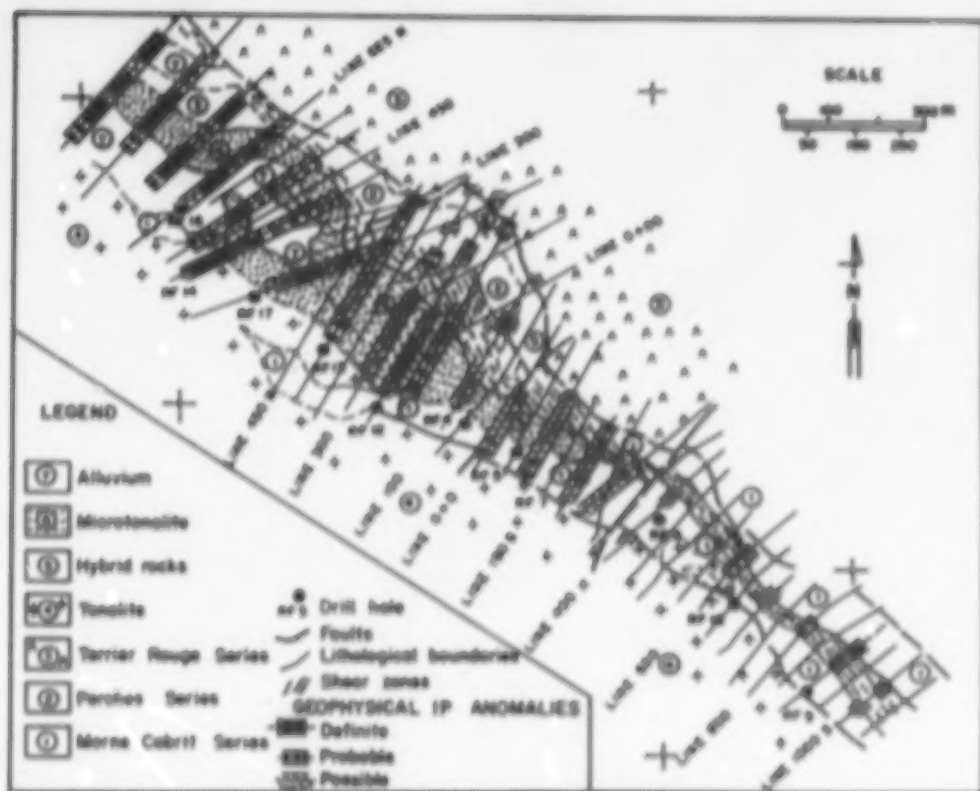


Figure 77.13. IP Geophysical plan of Faillie B.

Geological and geochemical data indicate two principal mineralizing events to have been active in the Faillie area. The earlier stratabound gold mineralization with sulphides and barite in the Perches Series is possibly related to hot spring activity. To date, this does not appear to be of economic importance, but it remains to be drill tested.

The later auriferous quartz veins appear to be genetically related to the microtonalite intrusives with which porphyry copper systems are also associated just to the north.

Textural and structural characteristics suggest syntectonic emplacement of the mineralization and intrusives, while post-mineral faulting has caused the present disposition of the various lithostratigraphic units in the form of tectonic slices.

The geochemical characteristics of the auriferous veins are similar to veins associated with dioritic intrusions in other active tectonic environments. The setting appears to be similar to some districts in California, for example Grass Valley, and Oregon, as well as to Dupont in northwestern Ontario.

The stronger development of quartz veins within the microtonalite stock is thought to be due to the relatively more brittle character of this intrusive

compared to the sheared metabasites and metasediments. Depletion of base and precious metals from the sheared and hydrothermally altered metasediments and metabasites, as well as the close association of gold mineralization with the metabasites, suggests that part of the gold in the quartz veins may have been regenerated from these older rocks.

Textural relationships of ore material suggest overlapping paragenesis of gold and vein constituents. The earlier phase of gold introduction is represented by the small inclusions of gold in pyrite and the later phase is associated with chalcopyrite and chlorite wisps and quartz. The common occurrence of gold on the selvages of sulphides or silicates suggests relatively late deposition or redistribution.

## CONCLUSIONS

Virgin gold-quartz vein mineralization of potential economic importance has been outlined at Faillie B. To date, the gold mineralization has been drill tested over a strike distance of 1.8 km.

In the Central Sector the gold resource in the quartzose material is estimated at 520 000 tonnes of 14 g/t Au, but the potentially mineable open pit reserve of 1.1 million tonnes is of much lower grade, in the order of 2.4 g/t. However, this could be



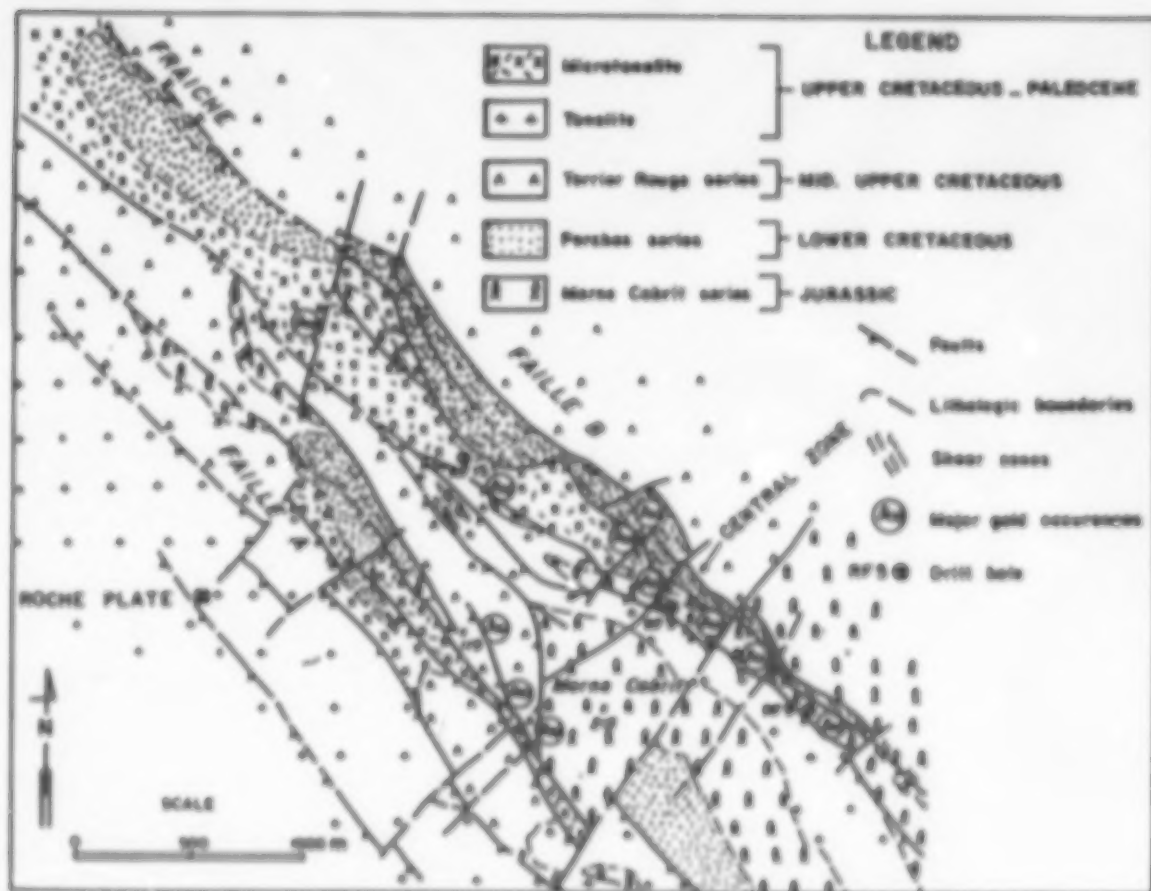


Figure 77.14. Geological map of Faillie tectonic belt.

"sweetened" with richer material at grass in the Alpha and Beta shoots.

The prospect warrants further assessment by saturation drilling or preferably underground exploration, leading to feasibility studies.

The possibility of additional gold resources undoubtedly exists at Faillie B, particularly in the southeastern end of the prospect which is still open. In addition, the faulted-off section is considered to be a viable exploration-drilling target at depth. Nearby, the Morne Cabrit auriferous quartz vein remains to be drill tested (Figure 77.14).

#### MAIN POINTS

1. Haiti has no mining industry at present, but geologically it is very favourable for many kinds of base- and precious-metal mineralization. The United Nations has put a significant effort into the country over the last 15 years, and it now looks as though three bedrock gold mines,

Milot, Grand Bois, and Faillie B, could be in production within the next few years.

2. Although Haiti is not known to have previously produced gold from bedrock mines, it can lay claim to the first gold or mineral discovery in the New World, when Columbus himself found alluvial gold in the northeastern part of the country in 1492.
3. This case history illustrates the importance of flexibility in exploration philosophy. The original precious-metal exploration models used, Pueblo Viejo and stockwork porphyry, did not come up to expectations. Instead, a different type of gold mineralization, which has not yet been graced with a name, was found.
4. This type is associated with high-level acid intrusives and ophiolites in major structural breaks associated with subduction zones along the periphery of batholiths, and appears to be similar in setting to Grass Valley, California, and Dupont, Ontario.

5. In the particular case of Faïlle B, geochemical exploration for Au in soils was the most useful technique for locating mineralization, although IP can claim one success in detecting deep sulphide with gold mineralization, which was not suspected based on surface geological and geochemical work.
6. The surfiferous quartz vein mineralization has been traced by drilling for 1.8 km of strike length and remains to be tested further.
7. Gold occurs as small particles of the native metal associated principally with copper sulphides. The Au:Ag ratio is 1.8:1 and Te is geochemically anomalous, although no tellurides have been recognized to date.
8. The apparently richer Central Sector of 300 m strike length is shaping up as both an underground or bulk open pit possibility. The amount of quartzose vein material in this sector has been

estimated at half a million tonnes of 14 g/t Au material.

9. The Fund Project has now finished its fieldwork and the Government is seeking proposals for the further exploration of the property.

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